

# Forward near-forward azimuthal correlations in p+p and d+Au collisions



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June 21<sup>th</sup>, 2012

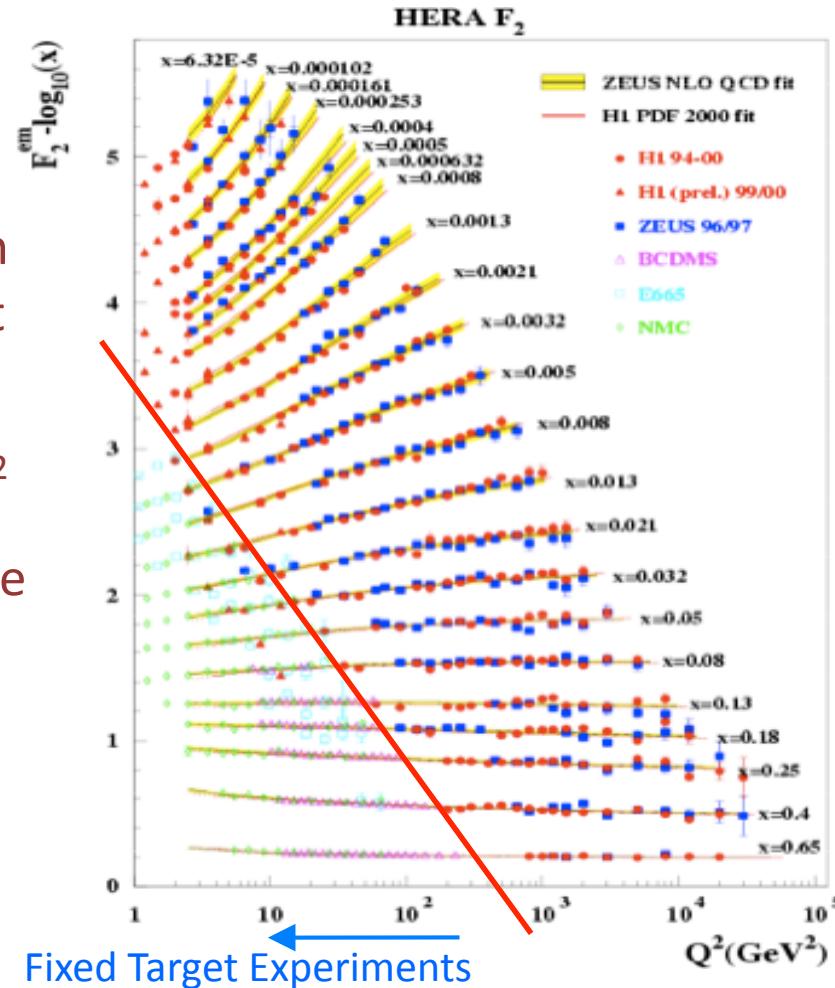
# Outline

- Introduction
  - Motivation
- Forward+near-forward correlations at STAR
  - FMS  $\pi^0$  – EEMC jet-like cluster azimuthal correlations
  - Correlations in pAu approach comparison with d +Au results
- Conclusions

# What does the nucleon parton distribution look like?

- The nucleon quark distribution is well known.

- Rapid rise of the gluon density at low- $x$  evident from  $\partial F_2(x, Q^2) / \partial \ln Q^2$ .
- $xg(x) \approx \partial F_2(x, Q^2) / \partial \ln Q^2$
- $F_2(x, Q^2)$  is the structure function at fixed  $x$ .

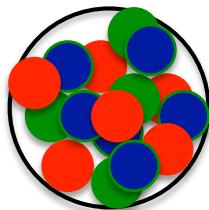


E. Rizvi, talk presented at the “International Euro Physics Conference on High Energy Physics”, July 2003

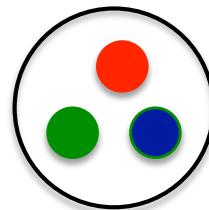
- The nucleon gluon density is derived from the structure function ( $x, Q^2$ ) and is well known in the  $0.0001 < x < 0.3$ .

# What does the nucleon parton distribution look like?

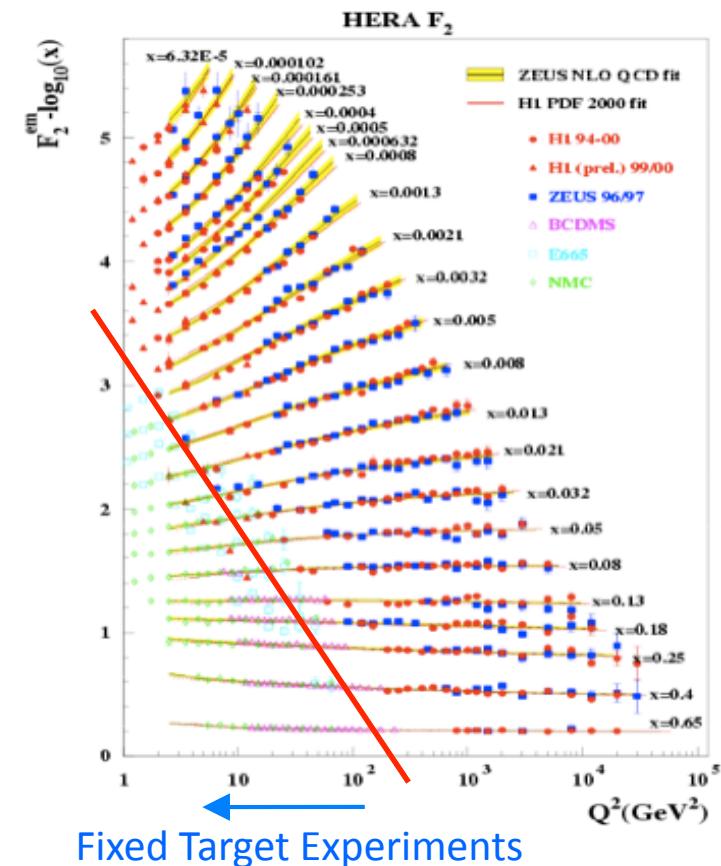
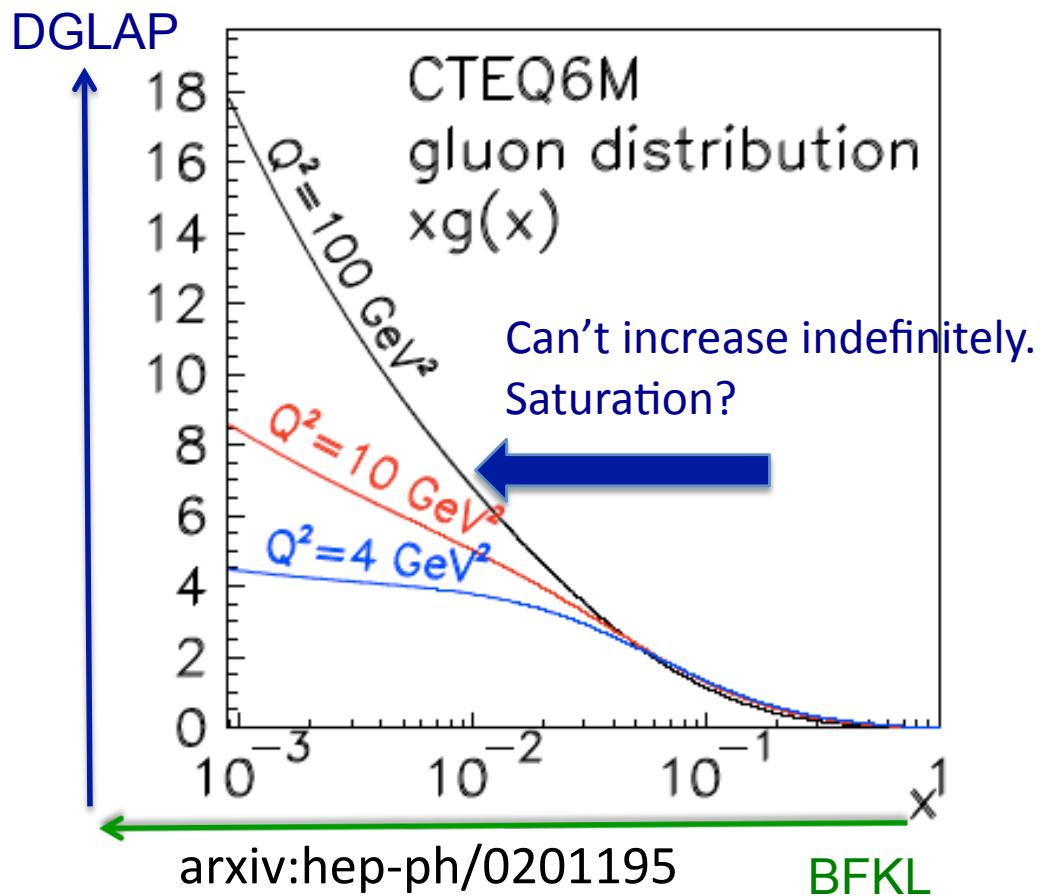
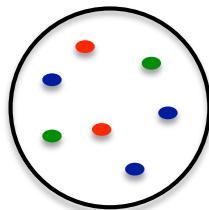
- The nucleon quark distribution is well known.



BFKL

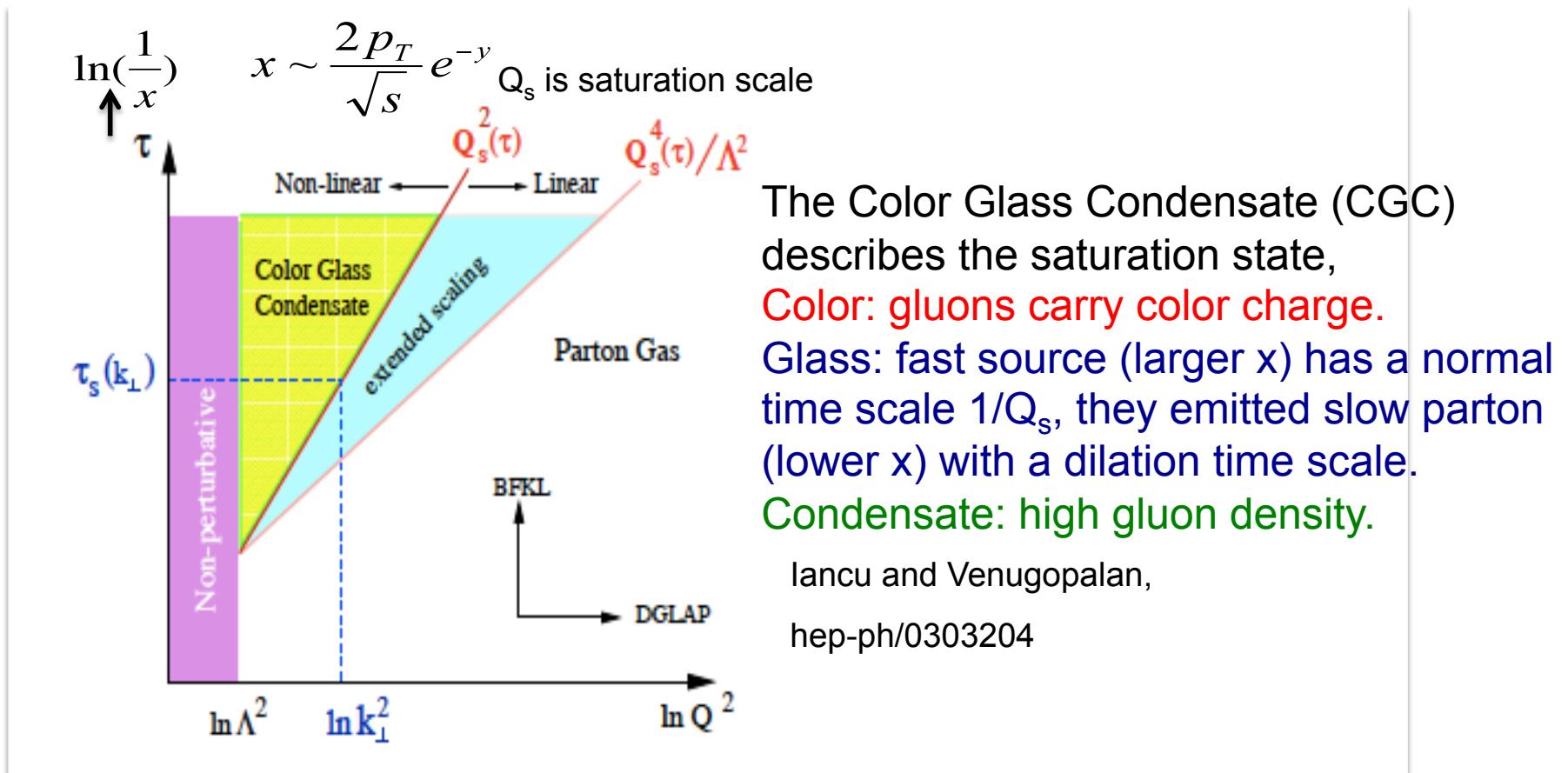


DGLAP



# What is the saturation state?

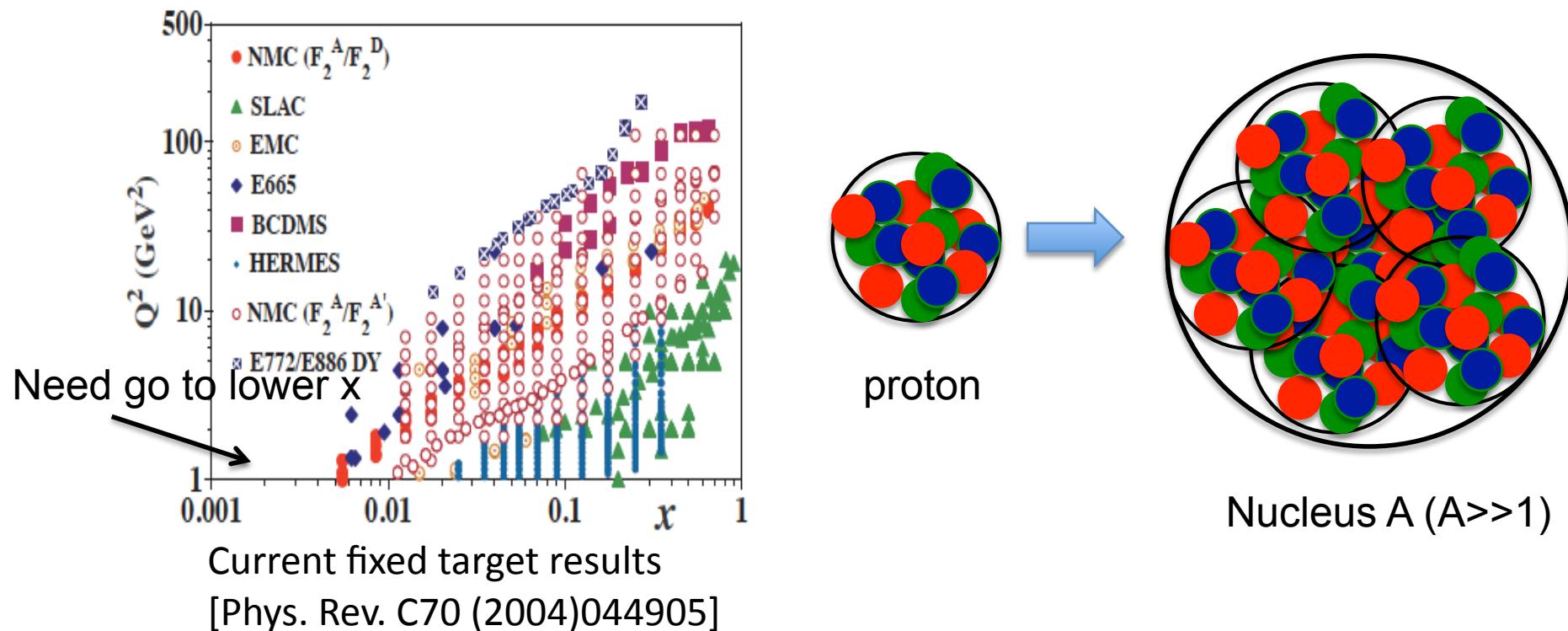
- When gluon recombination balances gluon splitting, saturation is realized.



- The nucleon gluon saturation is expected to be at  $x < 0.0001$  region.

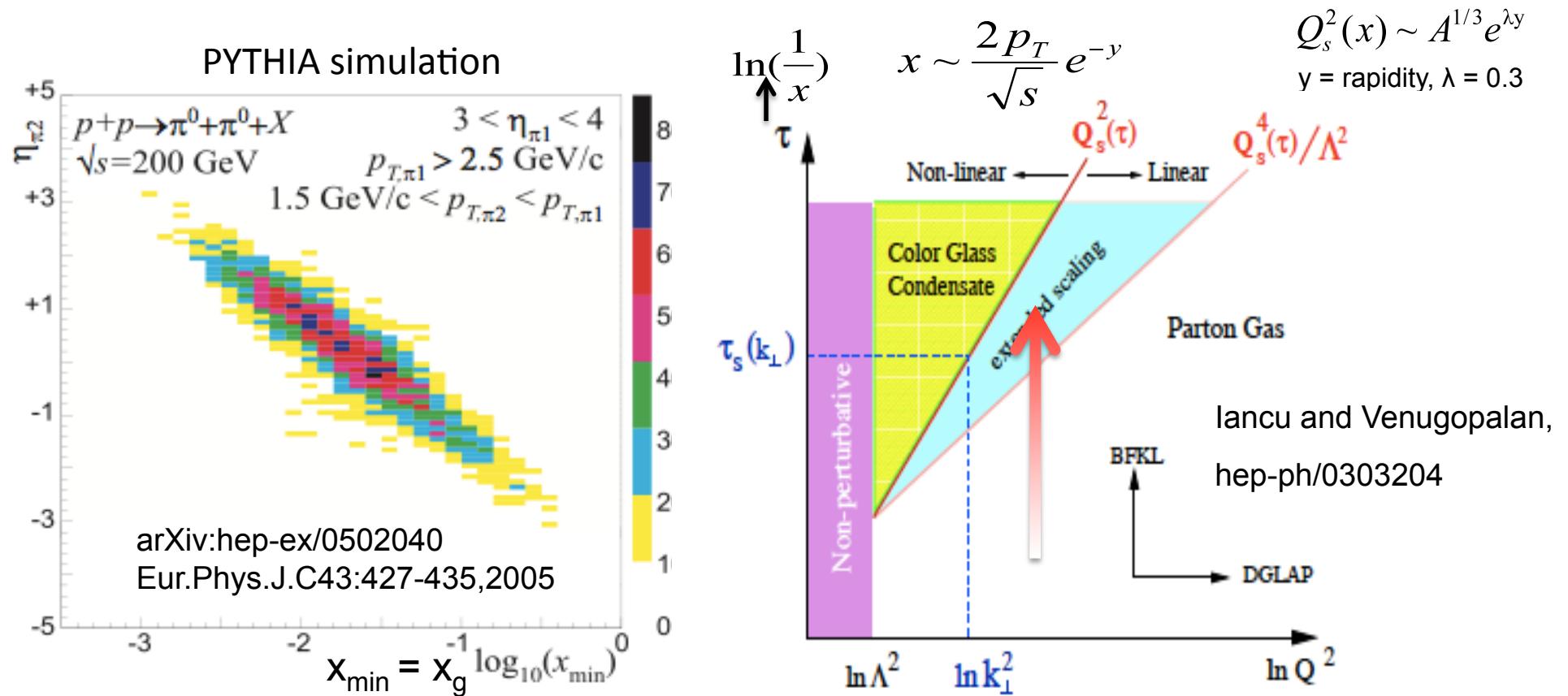
# How about a larger nucleus?

- Current fixed target experiments derived the nuclear gluon density only at  $0.02 < x < 0.3$ .



- Nuclear (mass number  $A$ ) gluon density  $\approx A^{1/3} \times$  nucleon gluon density at a given  $x$ , leading to the expectation  $Q_s^2 \approx A^{1/3} x^\beta$ . [hep-ph/0304189]  
For example, for Au nucleus, the saturation is expected at  $x \approx 0.001$ .

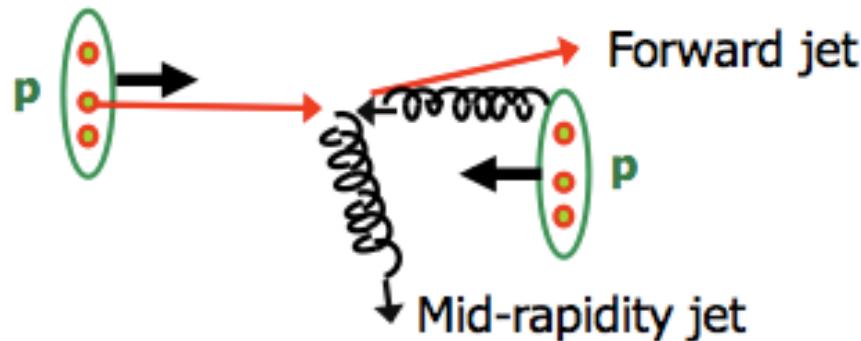
# The soft gluon $x$ is related to associated particle in correlations



- At fixed low  $Q^2 (> \Lambda^2)$ , the gluon density increases rapidly as  $x$  decreases. The state transfers from dilute parton gas to Color Glass Condensate (CGC).

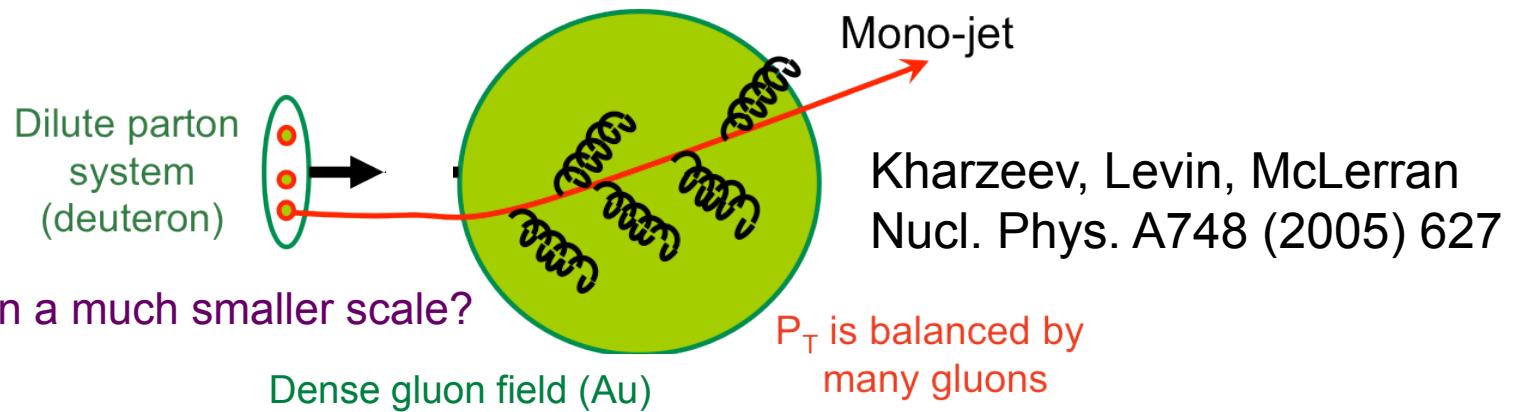
# Back to back correlations

- pQCD  $2 \rightarrow 2$  process =back-to-back di-jet (Works well for p+p)



- With high gluon density,  $2 \rightarrow 1$  (or  $2 \rightarrow$ many) process = Mono-jet ?

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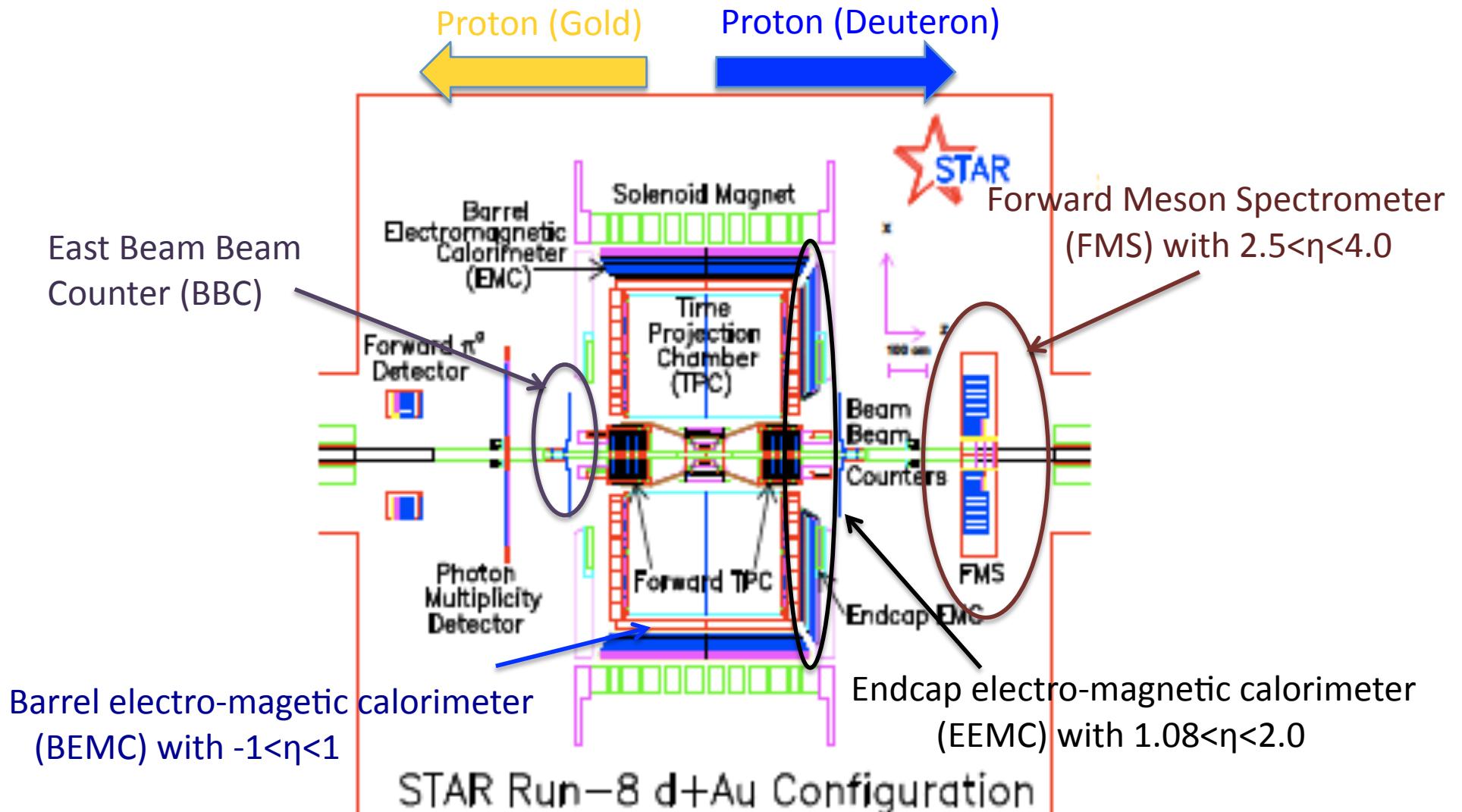


Mossbauer effect on a much smaller scale?

CGC predicts suppression of back-to-back correlation.

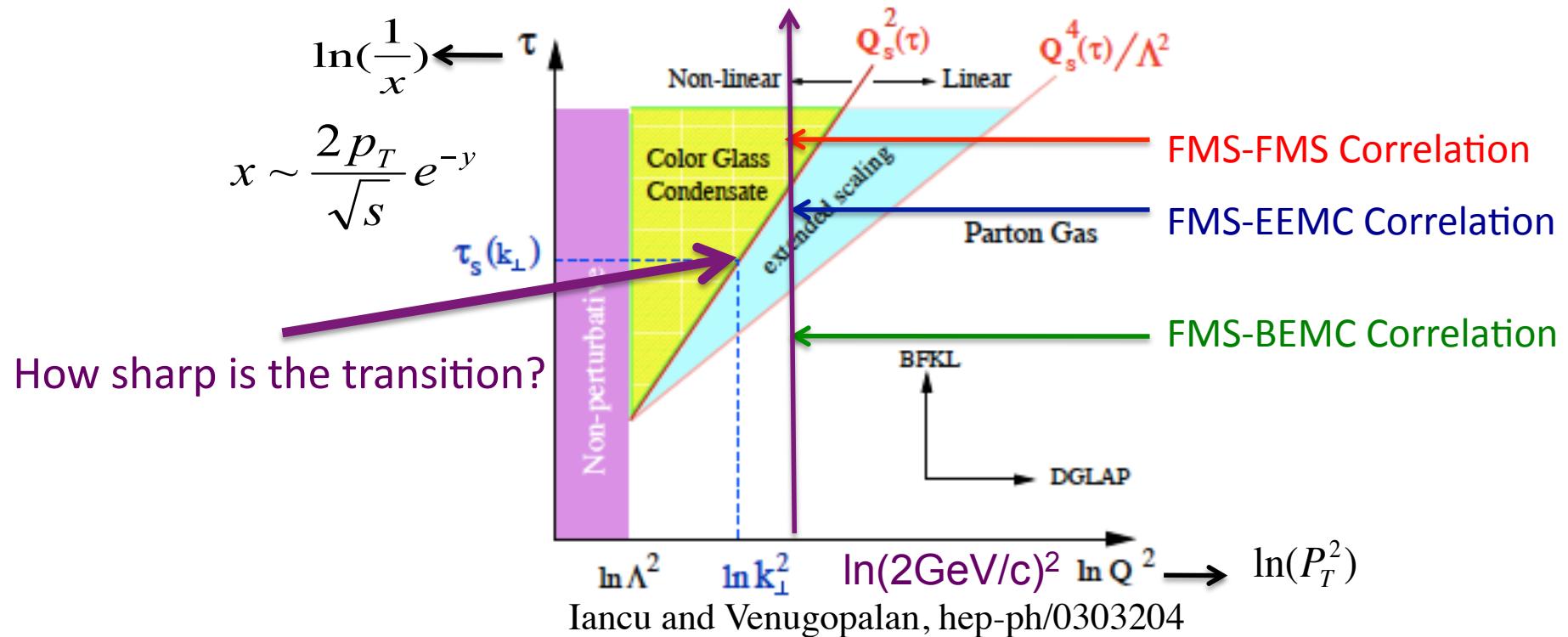
# STAR Detectors

- The schematics of STAR in RHIC run8.



# Rapidity dependence of azimuthal correlations

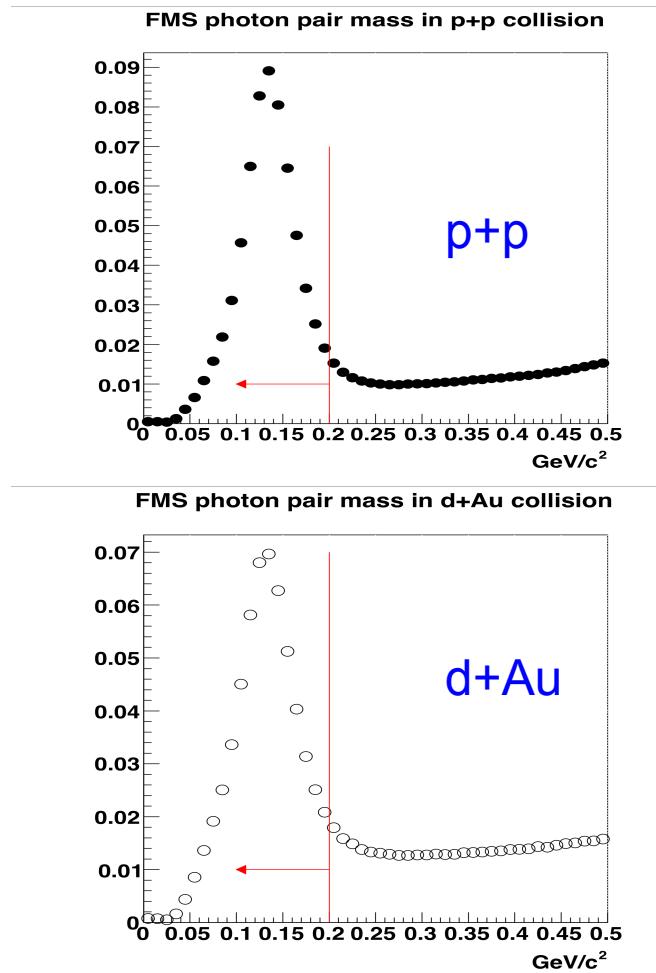
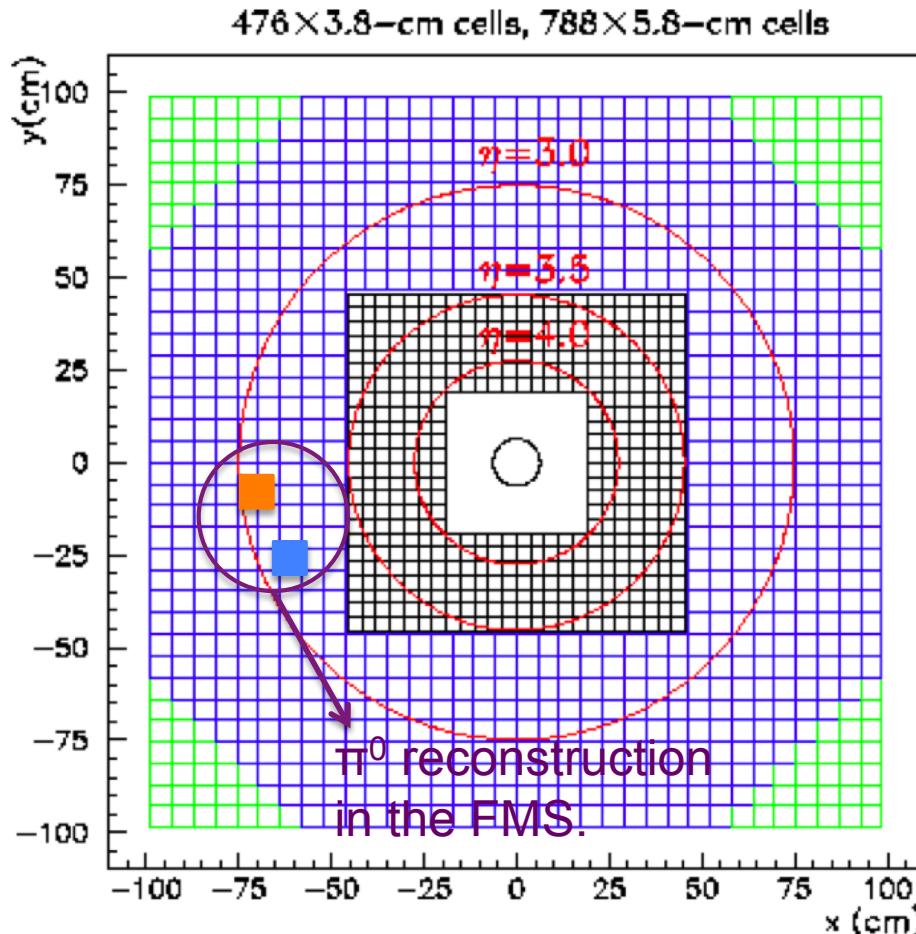
- At fixed low  $Q^2 (> \Lambda^2)$ , the gluon density increases rapidly as  $x$  decreases.



- Nearly continuous EM system (spans  $-1 < \eta < 4$ ) at STAR provides acceptance for azimuthal correlations at different pseudo-rapidity.

# $\pi^0$ reconstruction in the FMS

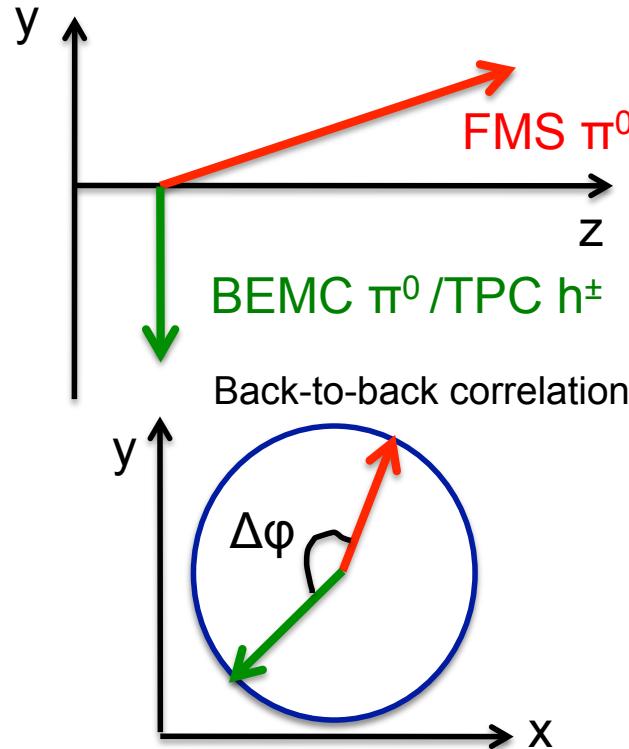
- The triggered particle is  $\pi^0$  reconstructed in the most forward detector — FMS.



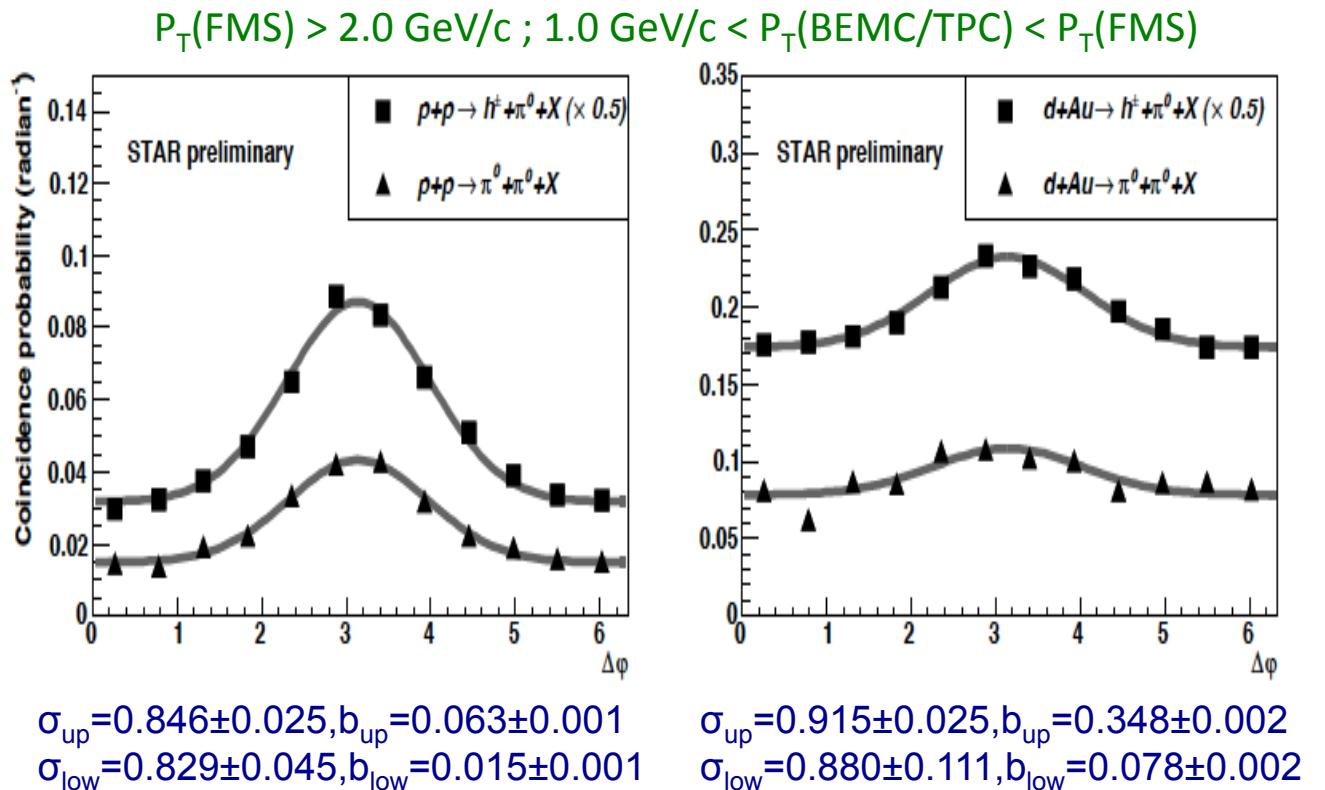
- There are clear  $\pi^0$  peak in the FMS during p+p and d+Au collisions.

# Forward-mid rapidity correlations

- FMS-BEMC(TPC) azimuthal correlations probe nuclei gluon density at  $0.008 < x_{\text{BJ}} < 0.07$ .



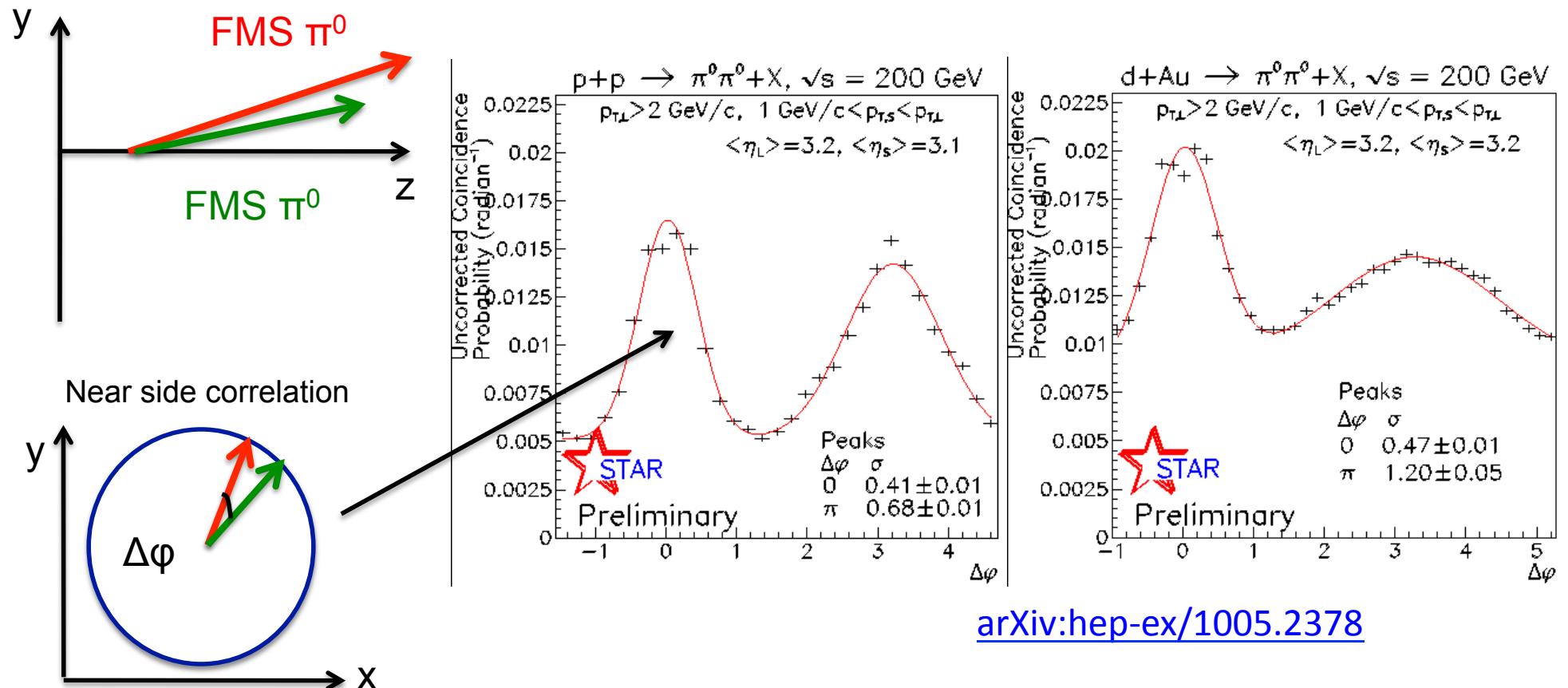
E. Braidot (arXiv:1102.0931)



- Higher pedestal in  $d+Au$  than in  $p+p$ .
- No significant broadening from  $p+p$  to  $d+Au$ .
- No hints of away-side peak disappearance.

# Forward-forward rapidity correlation

- FMS-FMS azimuthal correlations probe gluon density at  $0.0009 < x < 0.005$ .

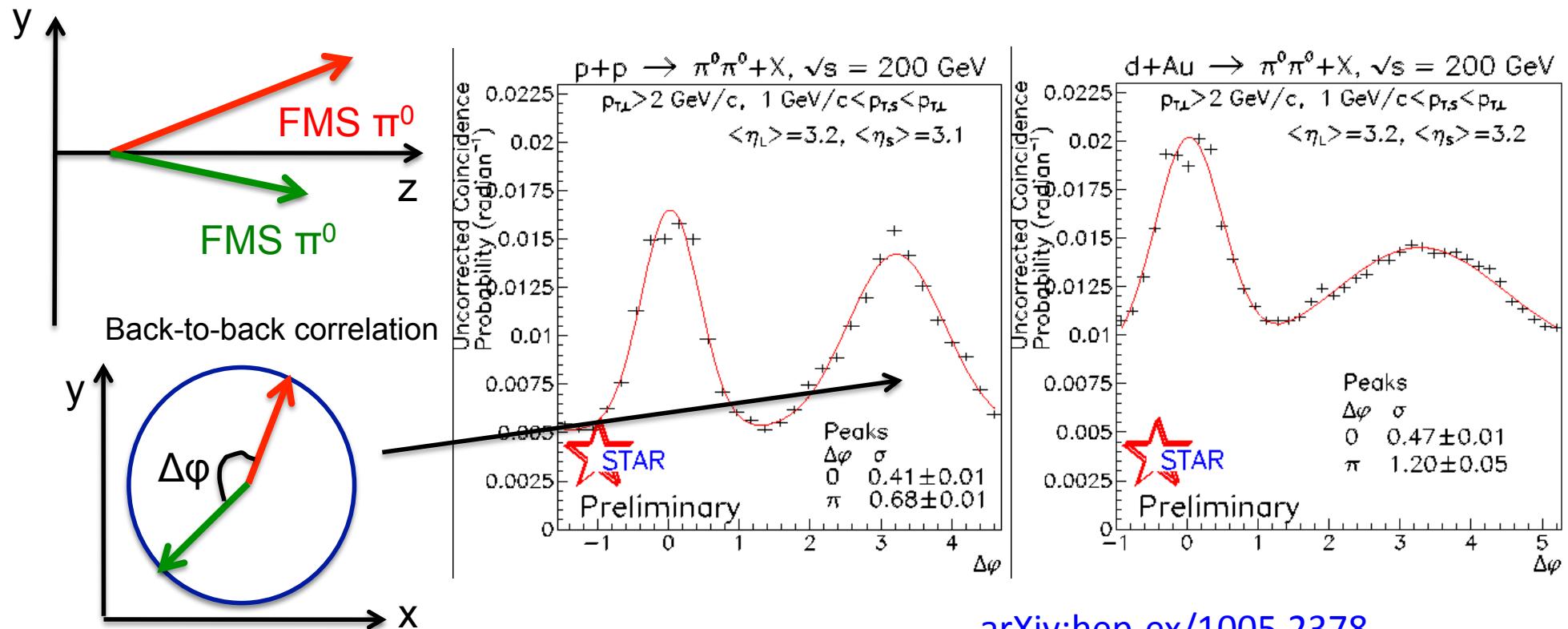


[arXiv:hep-ex/1005.2378](https://arxiv.org/abs/hep-ex/1005.2378)

- Similarity of near side peak in pp and dAu data.

# Forward-forward rapidity correlation

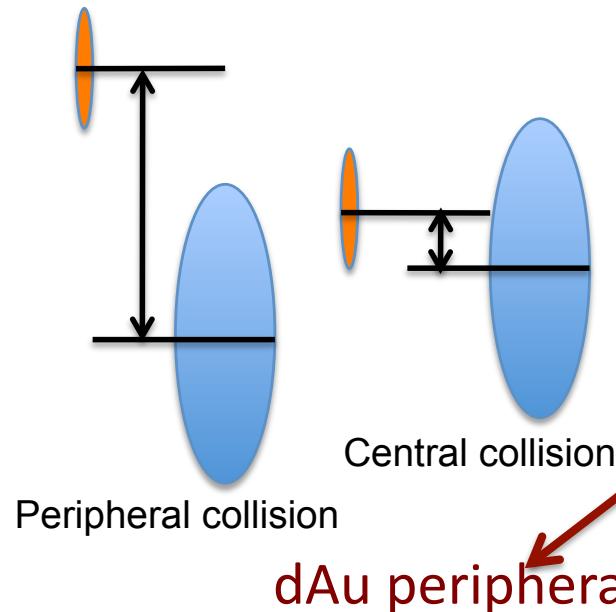
- FMS-FMS azimuthal correlations probe gluon density at  $0.0009 < x < 0.005$ .



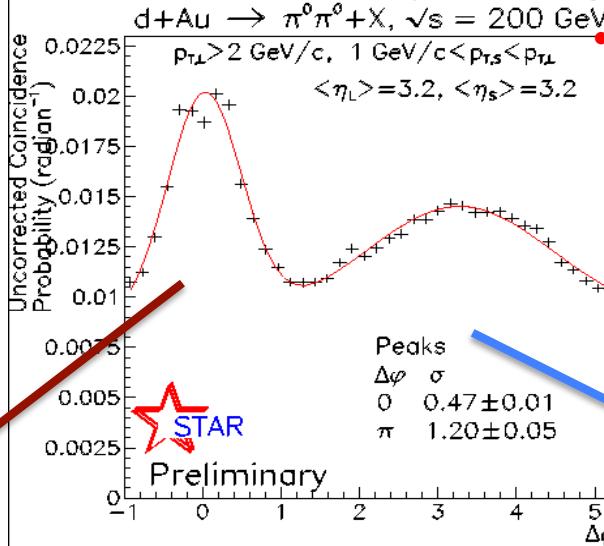
- There is significant broadening from pp to dAu in forward-forward rapidity azimuthal correlations in the away side peak.

# Forward-forward rapidity correlation

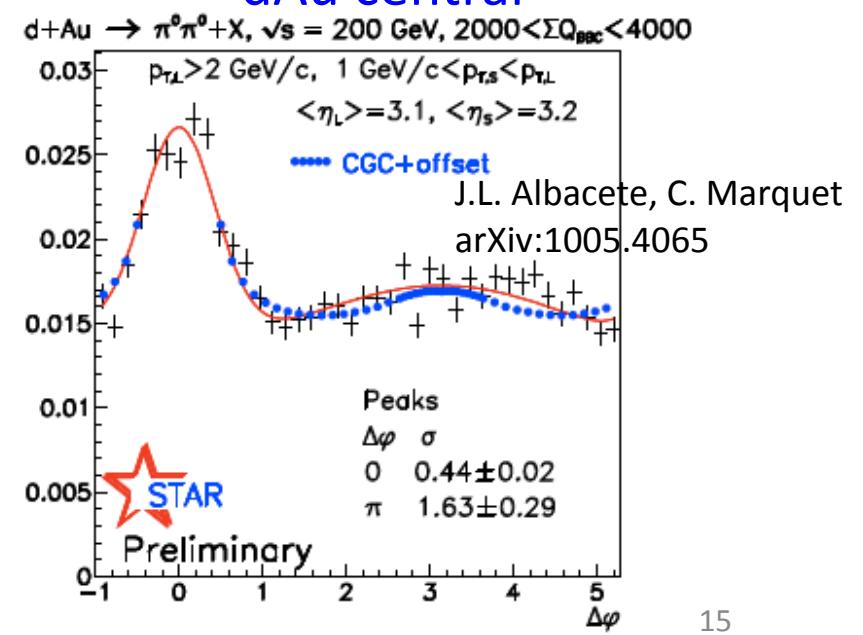
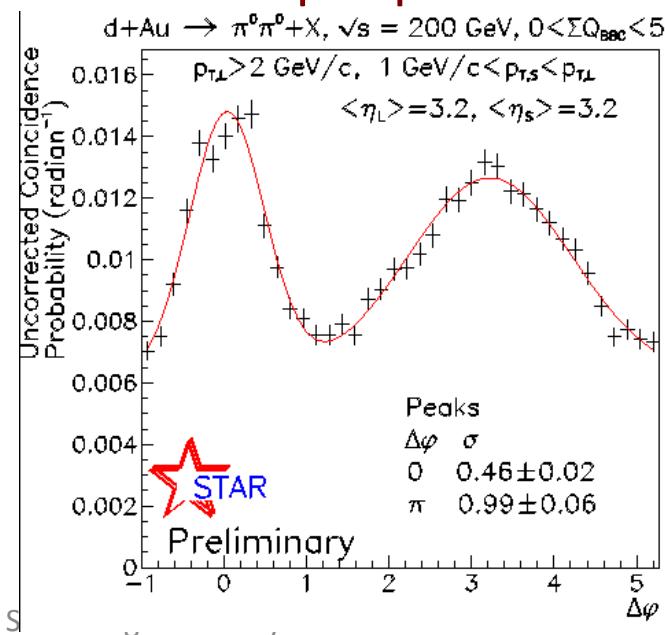
- Centrality cut on the dAu data.



dAu centrality averaged



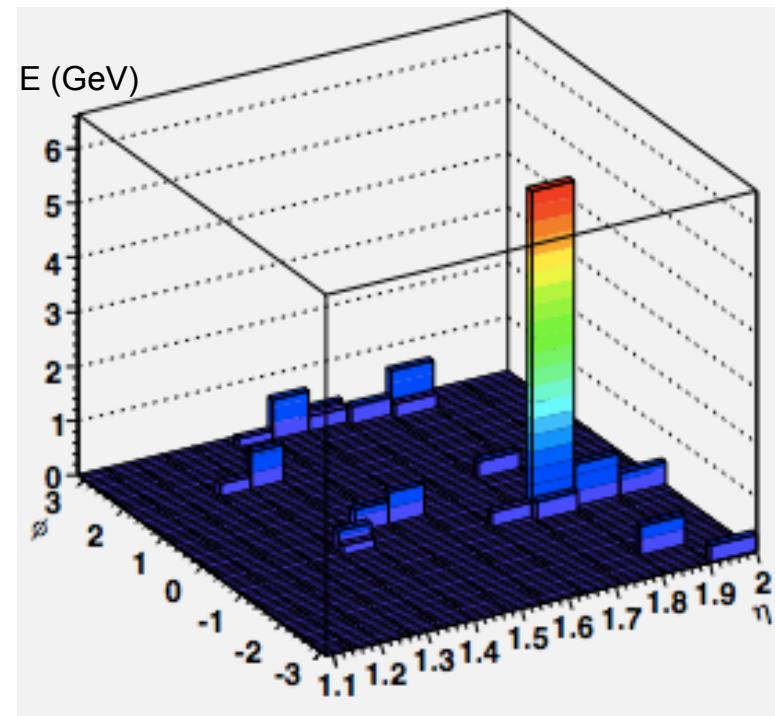
The suppression of the height of the away side peak in the central dAu collisions suggests forward-forward correlations at low  $x$  are consistent with gluon saturation in nuclei at RHIC.



# The event reconstruction in the EEMC

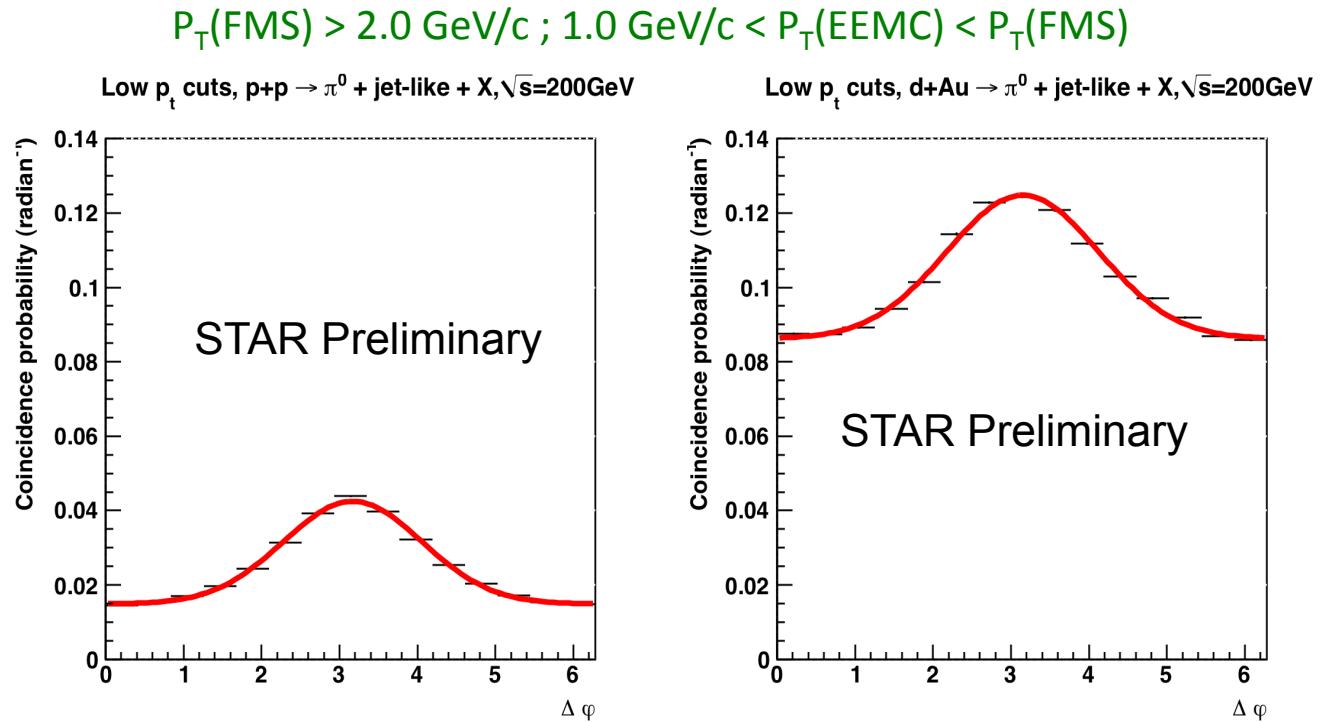
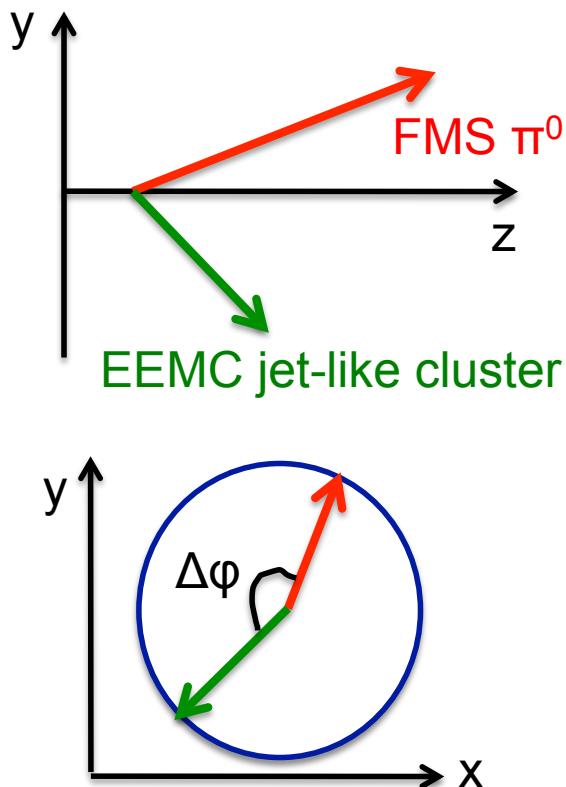
- The event is reconstructed based on the energy deposition in the EEMC.

One event of the energy deposition in the EEMC with FMS  $\pi^0$  trigger ( $p_t > 2.0 \text{ GeV}/c$ ) in  $p+p$  collision at  $\sqrt{s} = 200 \text{ GeV}$ .



- The  $\pi^0$  usually is the leading particle inside a jet measured in the EM calorimeter.
- The initial gluon state is independent of the final fragmentation process. Jet-like clusters can be surrogates of fragment partons.

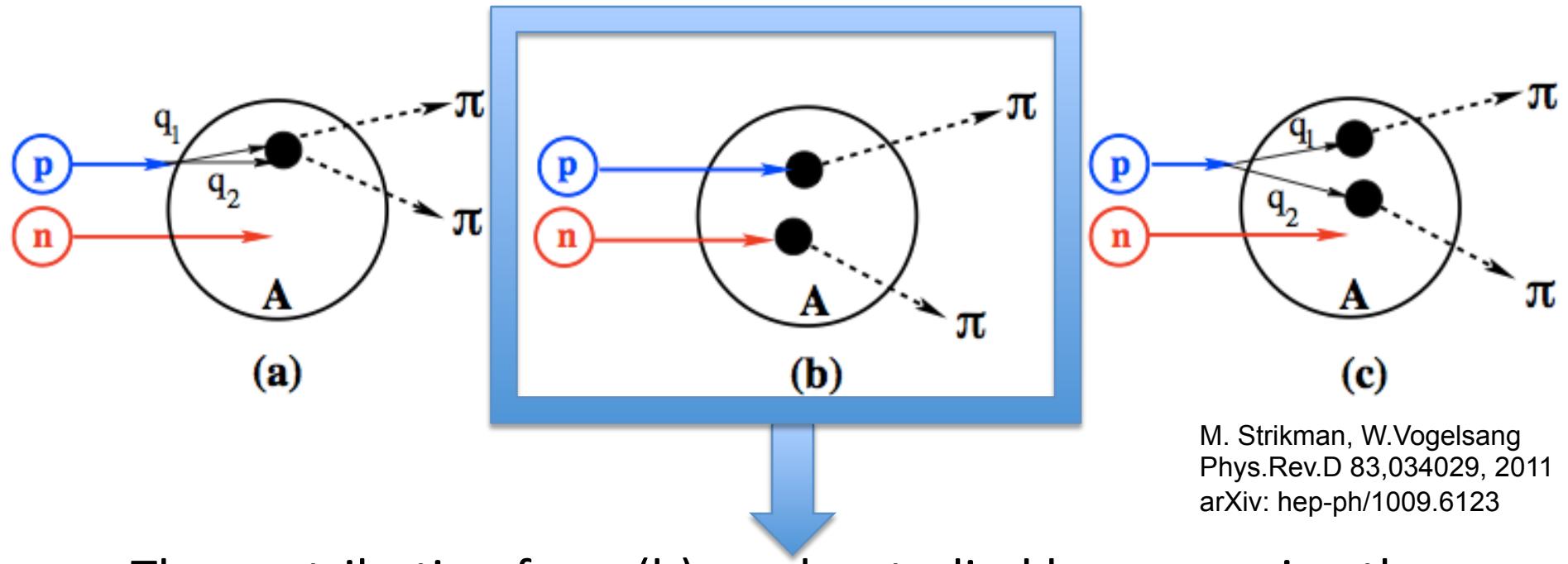
# FMS ( $\pi^0$ )-EEMC (jet-like cluster) correlations



- $\sigma_{d\text{Au}} - \sigma_{pp} = 0.081 \pm 0.012$ . Significant broadening from  $p+p$  to  $d+\text{Au}$  collisions.
- The gluon density ( $0.003 < x_{BJ} < 0.02$ ) is denser than the forward mid-rapidity region ( $0.008 < x_{BJ} < 0.07$ ).

# Theory predictions on the pedestal

- From leading twist to double parton scattering.

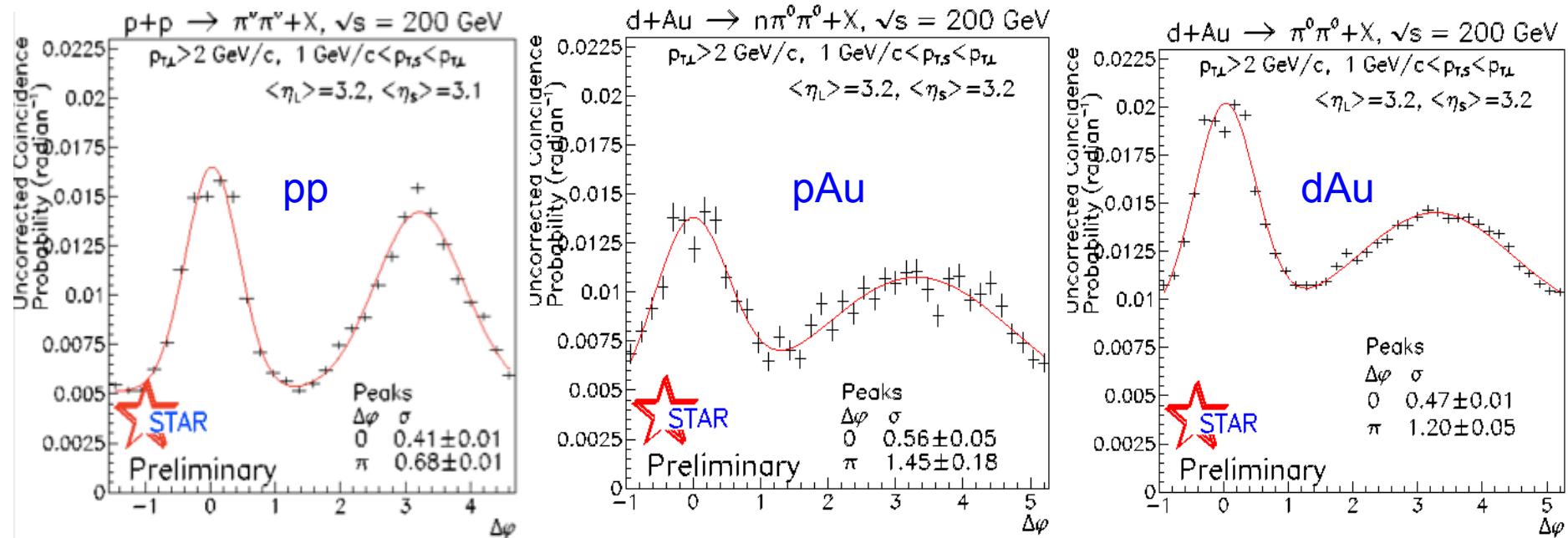


M. Strikman, W.Vogelsang  
Phys.Rev.D 83,034029, 2011  
arXiv: hep-ph/1009.6123

- The contribution from (b) can be studied by comparing the pedestal (uncorrelated part) of the correlations in d+Au and p+Au collisions.
- A deuteron beam facing neutron tag is used in d+Au collisions as a p+Au approach.

# What has been done in FMS-FMS correlations

- FMS-FMS  $\pi^0$ - $\pi^0$  correlations.

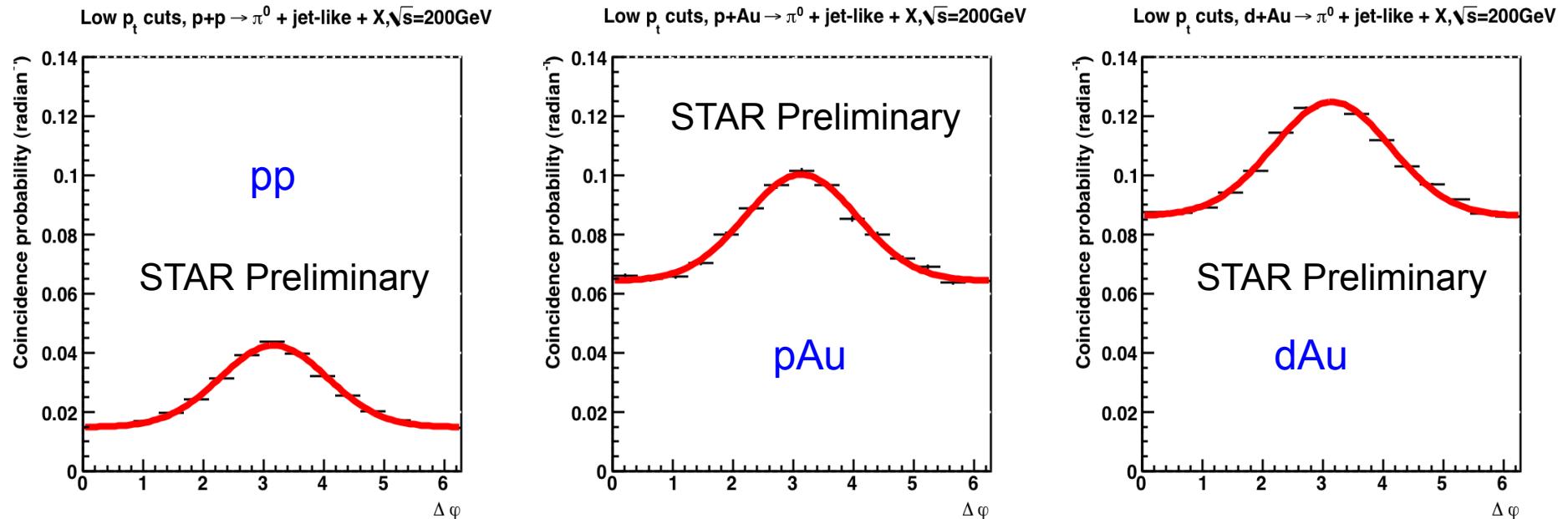


ArXiv:1109.0649

- Multi-parton interactions appear to contribute to the pedestal in d+Au collisions but not p+Au collisions.
- Other basic aspects of the azimuthal correlations appear to be unchanged between d+Au and p+Au collisions.

# FMS-EEMC correlations in p+Au approach

- The coincidence probability of azimuthal correlation.
- $P_t^{\text{FMS}} > 2.0 \text{ GeV}/c$  and  $1.0 \text{ GeV}/c < P_t^{\text{EEMC}} < 2.0 \text{ GeV}/c$  ( $M^{\text{EEMC}} > 0.2 \text{ GeV}/c^2$ )



- The p+Au approach only impacts on the pedestal, the other qualities like the width and the integral of the correlation peak are analogous like in d+Au collisions.
- The ratio defined as the correlation integral over the pedestal is comparable between this study and forward-forward analysis.

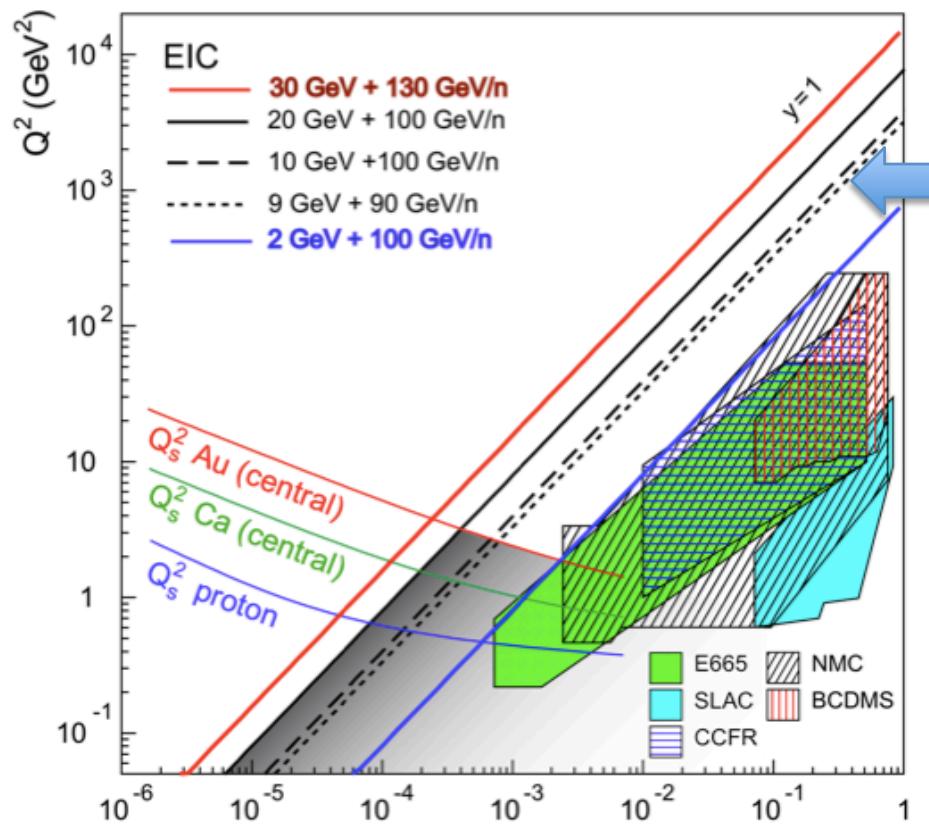
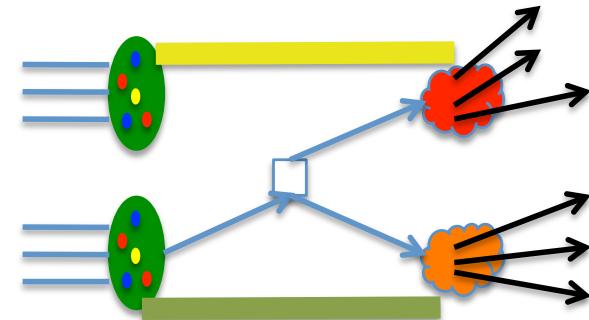
## Summary

- Significant broadening from p+p to d+Au collisions for the forward+near-forward correlations.
- The ratio of the pedestal in p+Au approach over the pedestal in d+Au collisions for the forward+near-forward correlations is comparable with the forward+forward correlations.
- The rapidity dependences of the correlations present a smooth transition process from dilute parton gas to dense CGC state.
- Further study is ongoing. Expect to present preliminary result in QM2012.

# Outlook of nucleus gluon saturation study

The final state  $\pi^0$ s or jet-like clusters are complex objects that can include not only color interactions from initial states but also from final states.

- A Electron Ion Collider (EIC)?

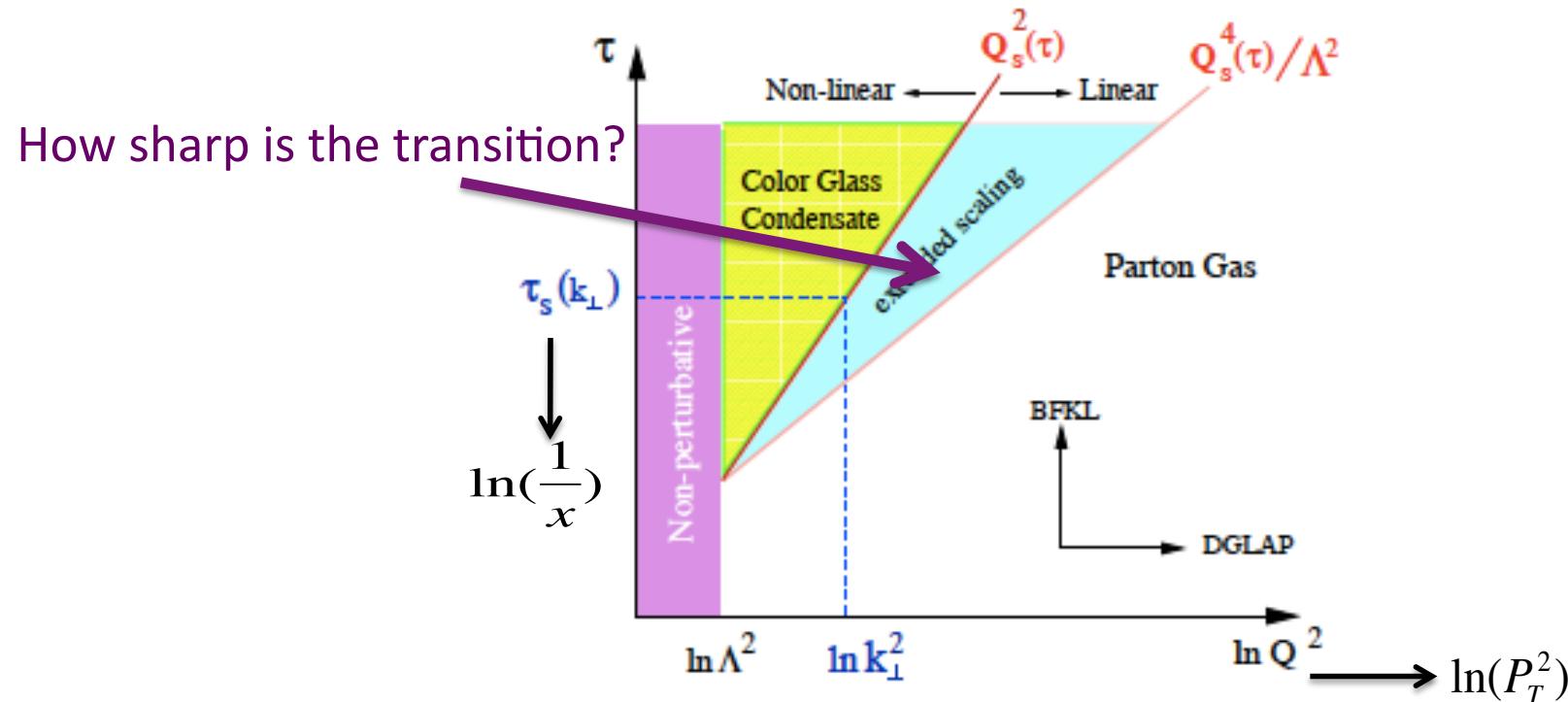


- Go to lower  $x$  than fixed target experiment.
- DIS process is much cleaner than the hadron-hadron interaction.

# Backup

# Gluon saturation is expected at low x

- Parton gas approach saturation through evolution.



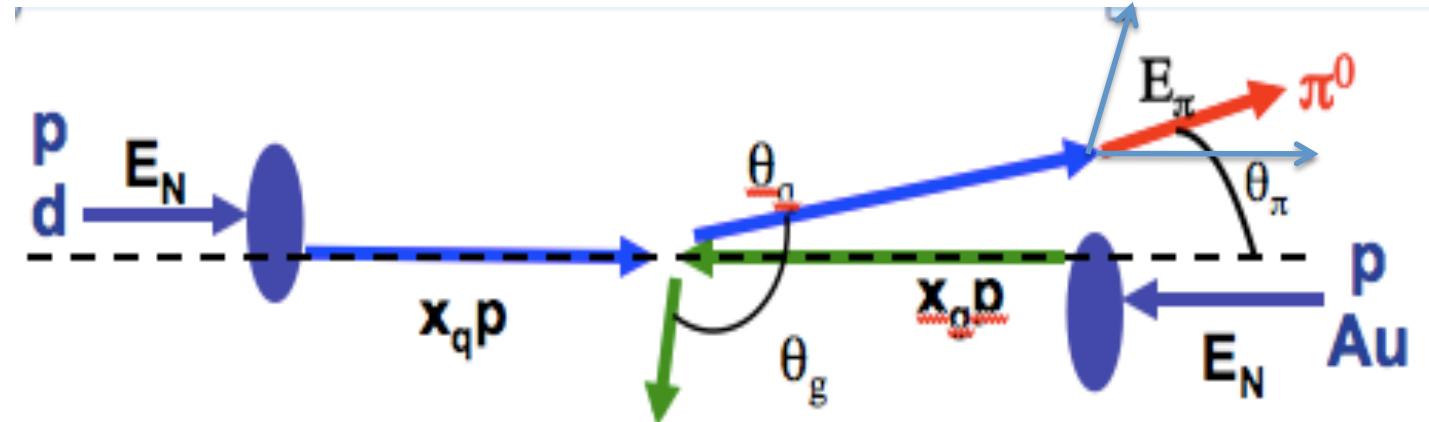
Parton saturation is expected at low x and low  $Q^2$ .

At a given x, nuclei (mass number A) gluon density  $\approx A^{1/3} \times$  nucleon gluon density, leading to the expectation  $Q_s^2 \approx A^{1/3} x^\beta$ . [hep-ph/0304189]

Current fixed target data provides  $0.02 < x < 0.3$  range for nuclear gluon density.

# How to probe low x gluons

- Forward inclusive production.



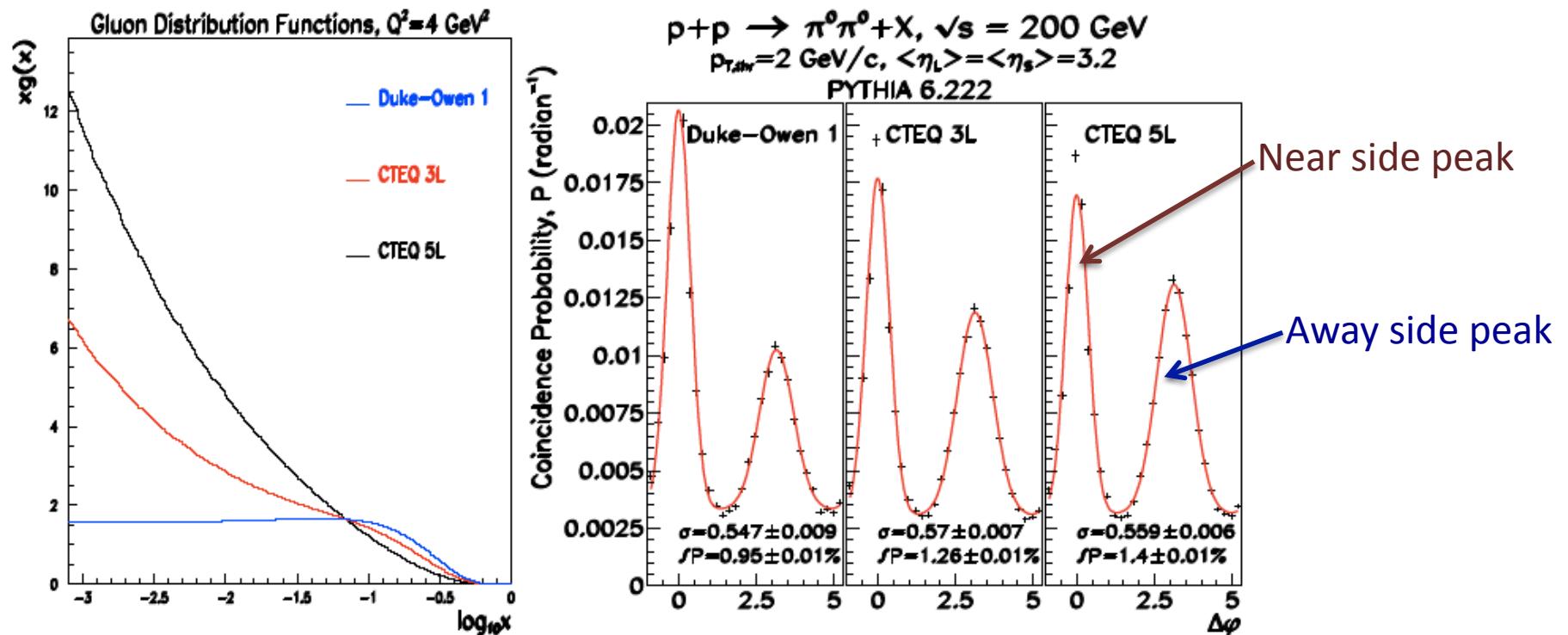
- The factorization mechanism is universal and can be applied in nucleon (nucleus)+ nucleon (nucleus) collisions.
- Large rapidity inclusive  $\pi$  production ( $\eta_\pi \sim 4$ ,  $\eta = -\ln(\tan\theta_\pi/2)$ ) probes asymmetric partonic collisions.**

$$x_q = \frac{p_T}{\sqrt{s}} (e^{+\eta_1} + e^{+\eta_2}) \xrightarrow{\eta_1 \gg \eta_2} x_F \quad x_g = \frac{p_T}{\sqrt{s}} (e^{-\eta_1} + e^{-\eta_2}) \xrightarrow{\eta_1 \gg \eta_2} \frac{p_T}{\sqrt{s}} e^{-\eta_1} \equiv x$$

- Mostly **high- $x_F$  valence quark + low- $x$  gluon.**

# How to measure the sensitivity

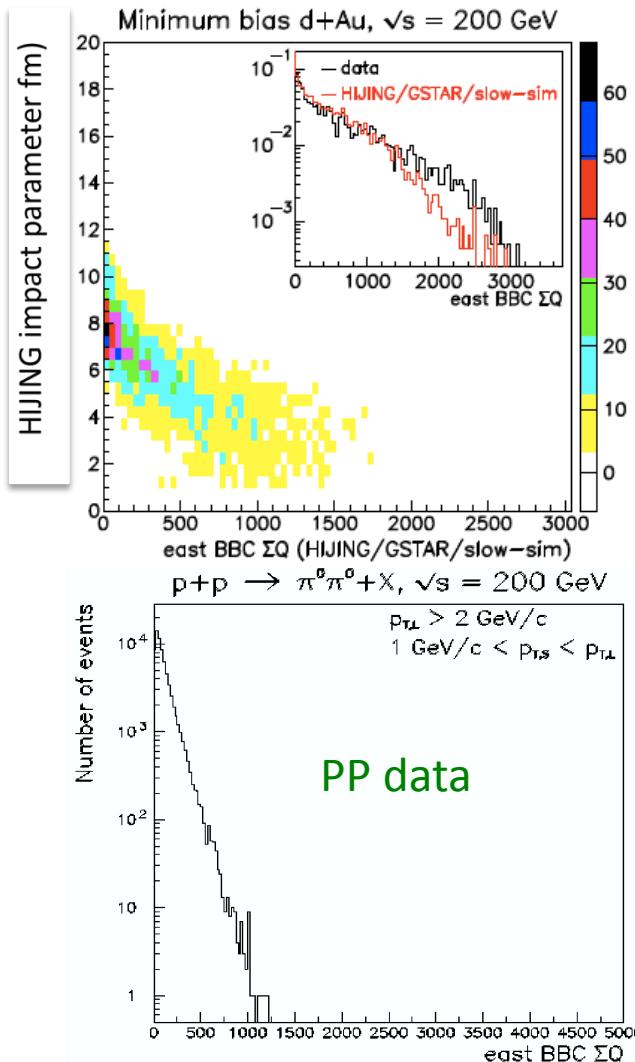
- Effects on the azimuthal correlations from different parton distribution for 2->2. scattering.



[arXiv:hep-ex/1005.2378](https://arxiv.org/abs/hep-ex/1005.2378)

The away side peak height is correlated with the parton density distribution in 2->2 scattering.

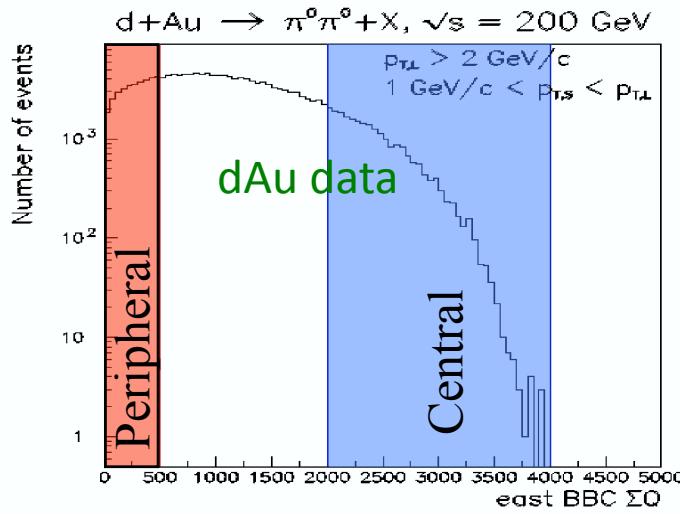
# Centrality determination in forward-forward rapidity correlation



The impact parameter is related with the charge sum in the east BBC by a model.

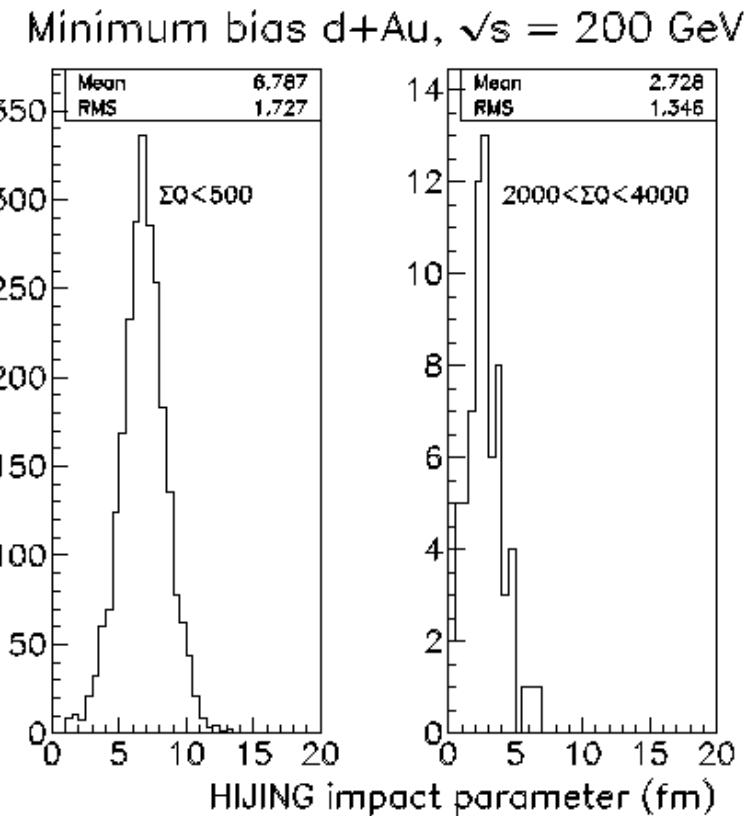
East BBC charge sum	Average impact parameter (fm)
0 - 500	$6.8 \pm 1.7$
2000 - 4000	$2.7 \pm 1.3$

[arXiv:hep-ex/1005.2378](https://arxiv.org/abs/hep-ex/1005.2378)



- Multiplicity in dAu measured by the east beam beam counter (BBC) at STAR reflects the centrality.

# Centrality cuts in dAu



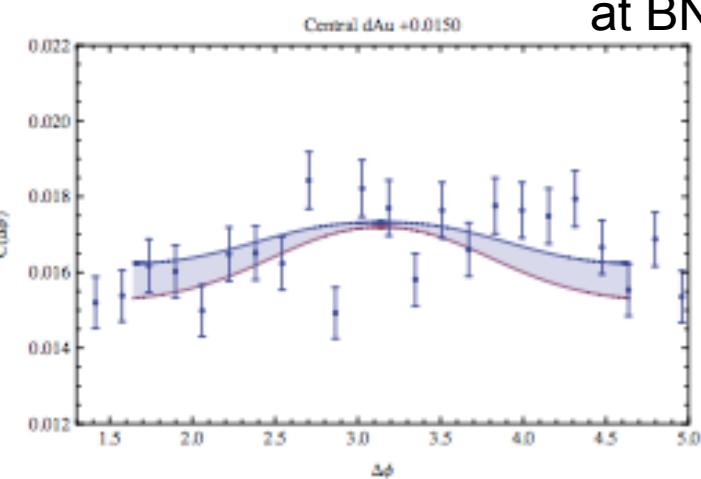
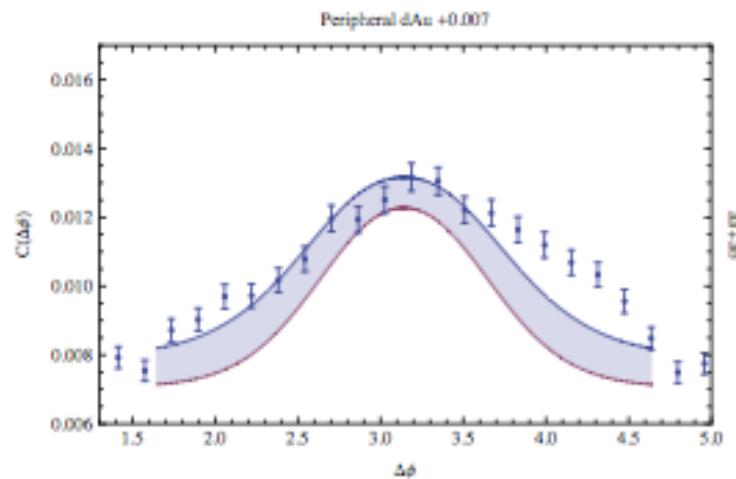
# Forward-forward rapidity correlation

- Centrality cuts.

Comparing to STAR data including both  $q + g$  and  $g + g$

[A. Stasto, BX, F. Yuan, in preparation]

For away side peak in both peripheral and central  $dAu$  collisions:

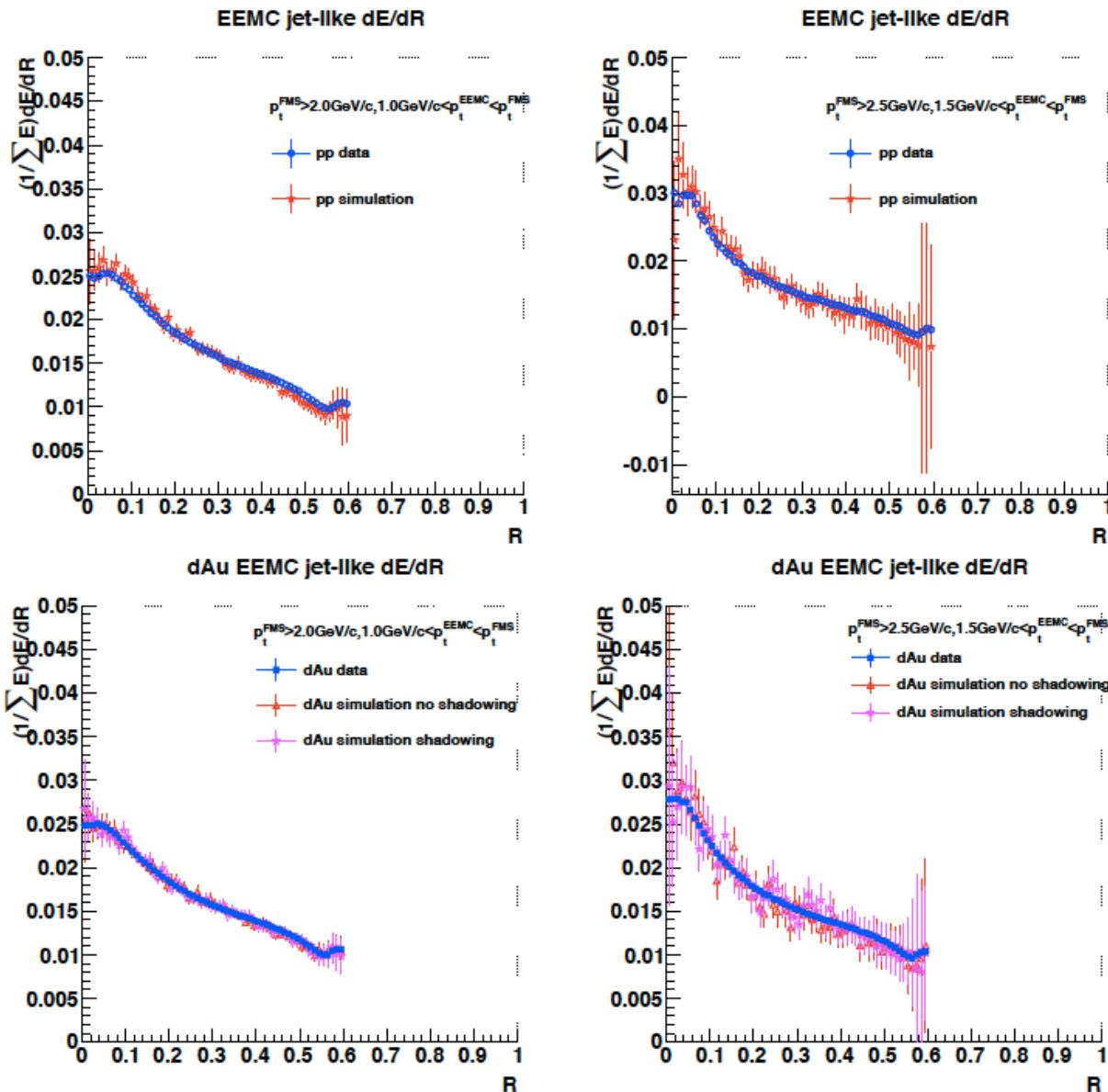


Bowen Xiao,  
Drell-Yan workshop  
at BNL

- Adding a  $k$ -factor of 2 to the ratio since the total single inclusive cross section is twice of the data at  $\eta = 3.2$ .
- Other parameters are kept the same.
- Both data and theory agrees well in peripheral and central  $dAu$  collisions.

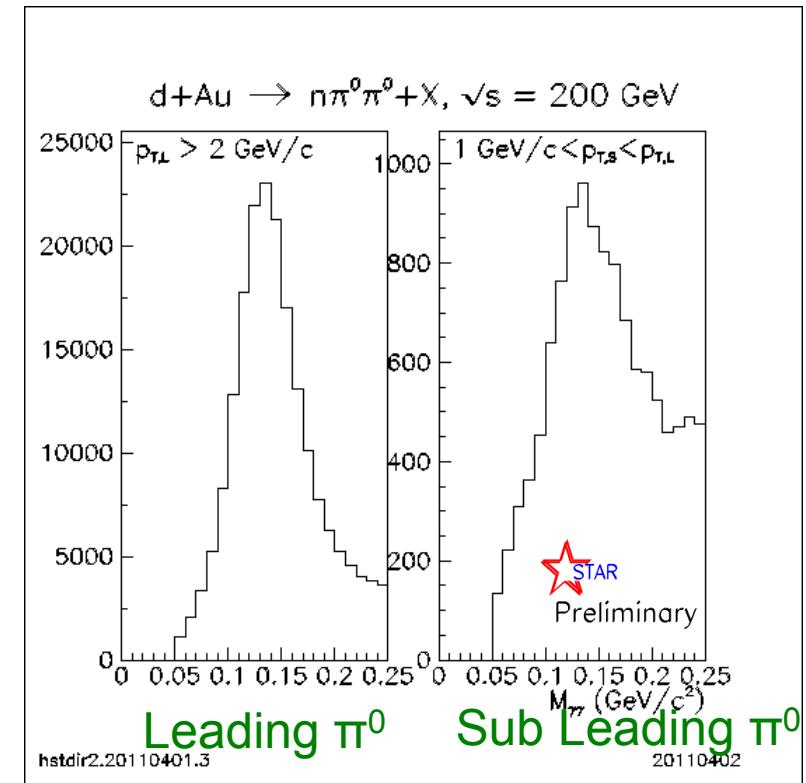
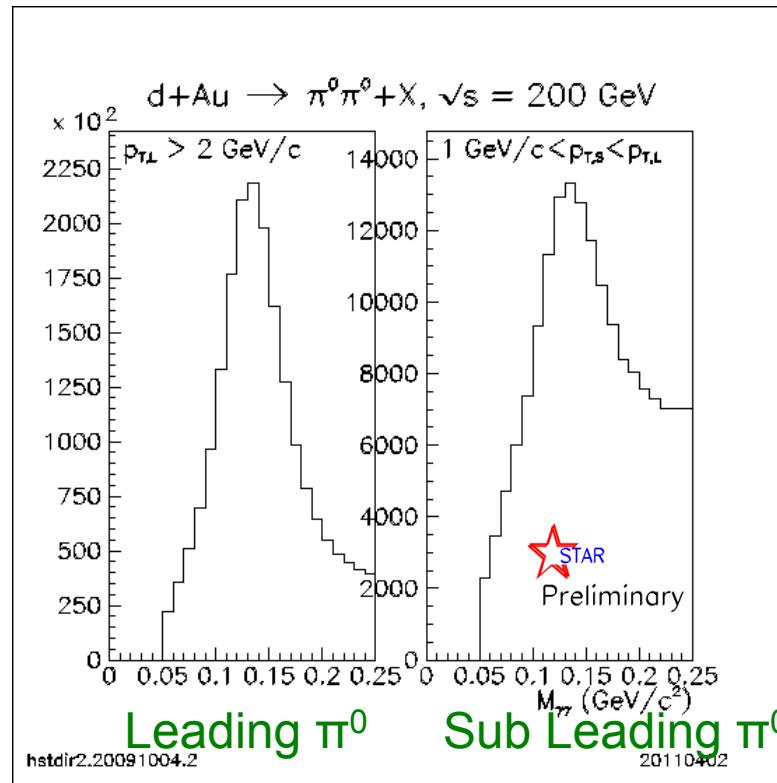
# EEMC jet-like cluster jet-shape

- With different  $p_t$  cuts in p+p and d+Au collisions.



# Di-Pion Invariant Masses

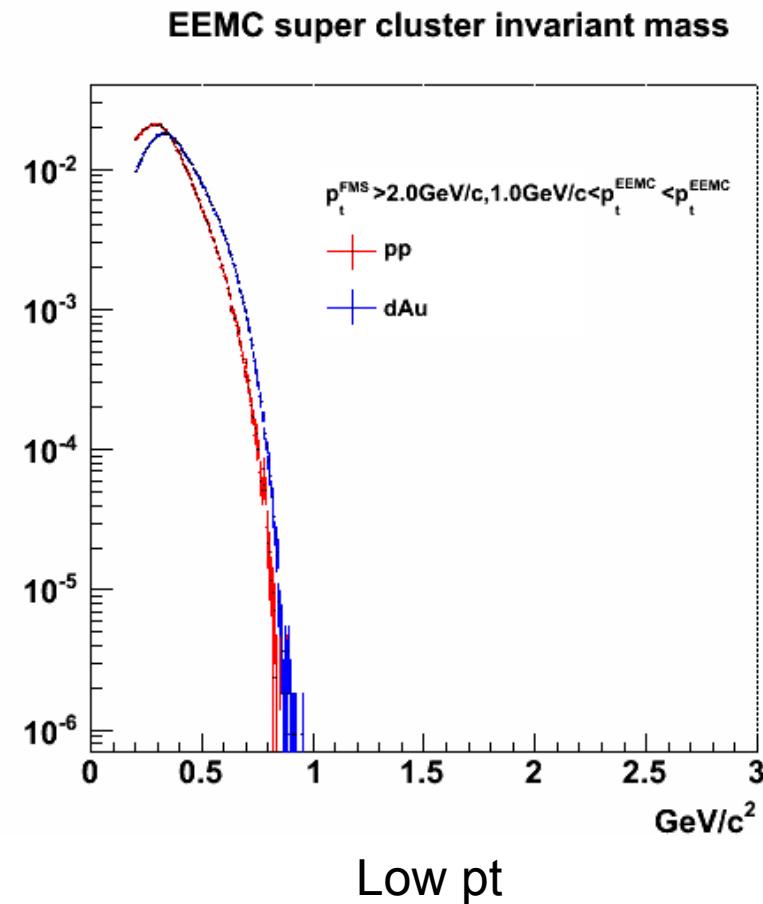
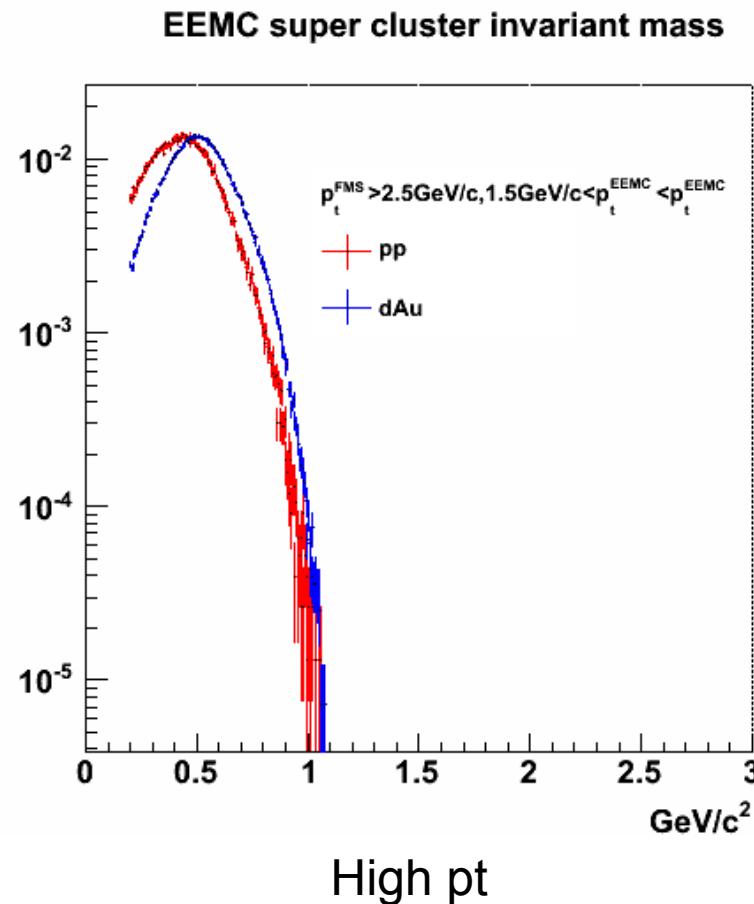
d+Au, Centrality Averaged, No Neutron Tag    d+Au, Centrality Averaged, With Neutron Tag



- Similar Invariant Mass distributions with and without neutron tagging
- Efficiency Corrections of Azimuthal Correlations should be similar with and without neutron tagging

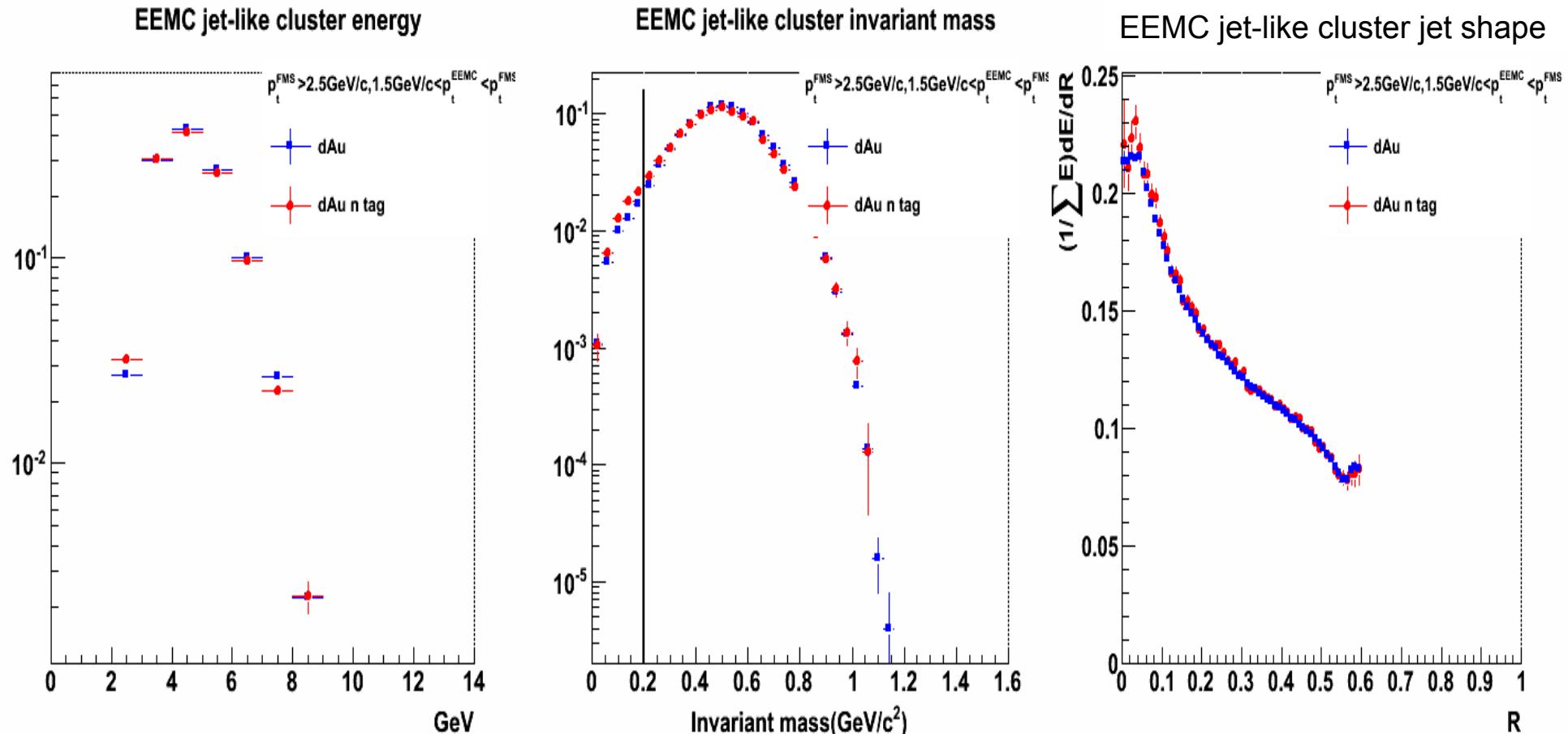
# Comparison between pp and dAu

- EEMC jet-like cluster invariant mass.



# ZDC n tag (higher $p_t$ )

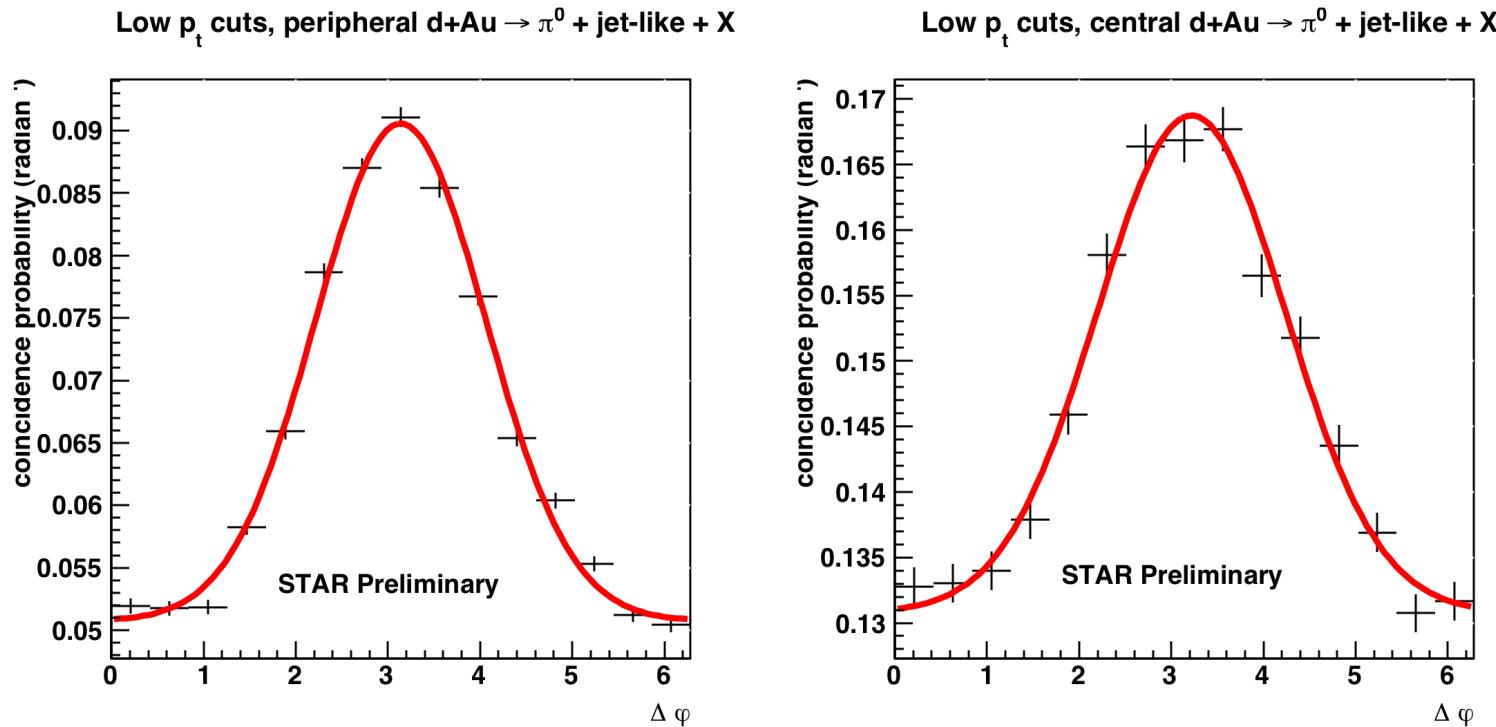
- The jet-like cluster in dAu and pAu (ZDC n tag).



- For E, M and  $(1/E)dE/dR$ , dAu and pAu (ZDC n tag) look similar.
- ZDC n tag doesn't introduce further bias on efficiency studies.

# FMS ( $\pi^0$ )-EEMC (jet-like cluster) correlations

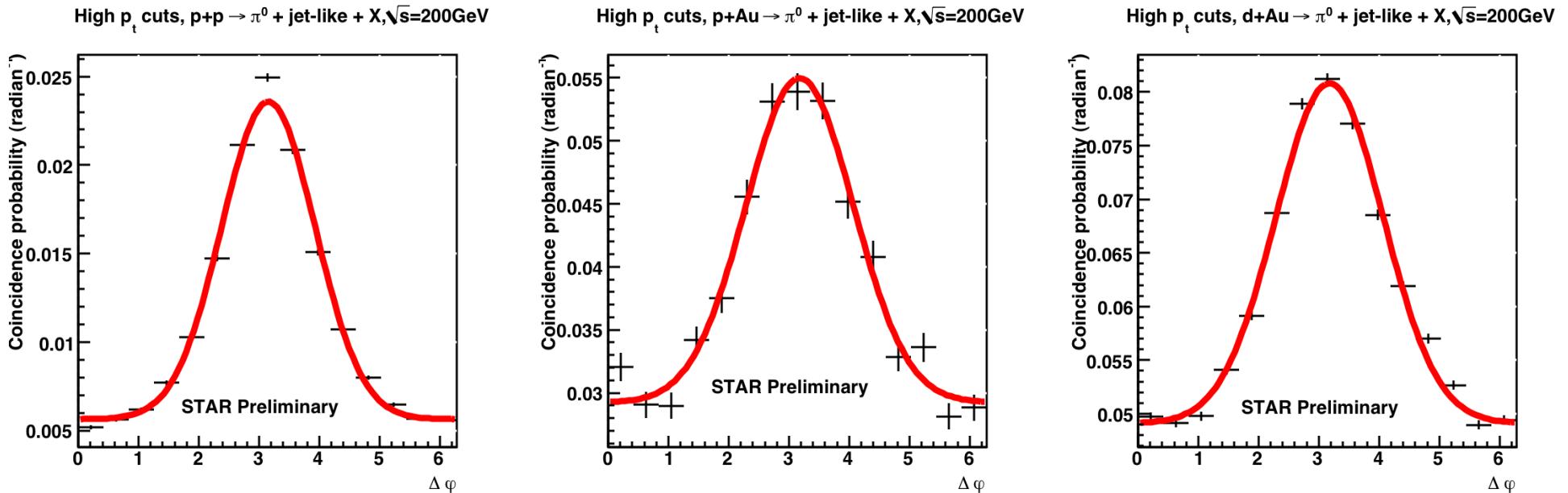
- Centrality dependence



- The correlations in central d+Au collisions are broader than in peripheral d+Au collisions.

# FMS-EEMC correlations in p+Au approach

- The uncorrected coincidence probability of azimuthal correlation.
- $P_t^{\text{FMS}} > 2.5 \text{ GeV}/c$  and  $1.5 \text{ GeV}/c < P_t^{\text{EEMC}} < 2.5 \text{ GeV}/c$  ( $M^{\text{EEMC}} > 0.2 \text{ GeV}/c^2$ )



- The p+Au approach only impacts on the pedestal, the other qualities like the width and the integral of the correlation peak are analogous like in d+Au collisions.
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